CONTROL ALGORITHMS FOR DISTRIBUTED NETWORKED INDUSTRIAL SYSTEMS

BY

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A Dissertation Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In

SYSTEMS ENGINEERING

DECEMBER 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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عمادة الدراسات العليا
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To the memories of my beloved parents, Muhammad Shafi & Mumtaz Bagum; which are sustaining me through the journey of life.

To my sisters, Tahira & Saira; my brothers, Muhammad Rafi, Muhammad Sami, & Muhammad Mutee, and all the nephews & nieces.

&

To my best friend Ayesha for everything she brought in my life, and my wonderful daughters Aaliyah & Juweriyah for their love, and being my best cheerleaders.

ACKNOWLEDGMENTS

In the name of Allah, the Most Beneficent, the Most Merciful

All praise is to Allah, the Almighty alone. May the Peace and Blessings of Allah be upon the Messenger of Allah (Sallal-Laho-Alaihi-Wasallam), his family, and his companions (Radhi Allah Anhum).

I am grateful to extend my gratitude to my dissertation adviser, Distinguished Prof. Magdi S. Mahmoud, for his continuous help, guidance, patience, and much needed attention and encouragement. His valuable suggestions and guided discussions were the key to focus and completing the work. I am also thankful to my dissertation co-adviser Prof. Moustafa Elshafei for his humble and valuable guidance whenever I needed. I am equally grateful to my dissertation committee members Prof. M. A. Habib, Prof. Fouad M. Al-Sunni and Dr. Sami Elferik for their guidance, prompt discussions, useful comments and support in all matters. I deeply appreciate the department chairman Prof. Fouad M. Al-Sunni for his support in every matter and providing us a conducive environment for research and studies in the department.

I am very thankful to everyone in the department for their kindness and support. I like to thank and appreciate the hours and discussion with my good friends

Tariq, Azhar, Ahmed, Bilal, and Ameen to name few.

I believe that every success I enjoyed carries the prayers of my parents. May Allah bless my parents. The presence of my parents in my thoughts is the key motivation for doing good while giving the feeling of their kindness. I am also thankful to my brothers and sisters for their encouragement and support. I am much much grateful and appreciate my wife and children for their patience, help and kindness during the whole period of studies.

Finally, I would also like to thank the Deanship of Scientific Research (DSR) at KFUPM for financial support through the research group project RG-1316. I would also like to appreciate the support, facilities, and people at KFUPM that made this work possible.

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DISSERTATION ABSTRACT

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MAJOR FIELD:	Systems Engineering
DATE OF DEGREE:	December 2013

Distributed control system comprises many nodes (i.e., controllers, sensors, and actuators), which are interconnected with communication networks. The control networks in industry have evolved from dedicated communication links to distributed communication links over shared data networks. Typically, the control and communication systems in a distributed networked industrial system are based on periodic sampling. This may result in excessive use of communication and computational resources causing high network traffic. The increased network traffic can cause delay, packet drop, and network congestion problems which affect the performance and stability of control loops over the network. This thesis proposes an event-based solution to reduce the network traffic and to avoid the delay, and packet drop in the context of distributed networked control systems.

The thesis studies event based control systems and communication scheme in output-feedback framework and with application to wireless communication network. Initially, the simulation and experimental investigation is conducted in the framework of distributed networked systems. A general output-feedback based framework is proposed for event-triggered transmission and control. Locally distributed observers estimate the states from the locally available data and make decision for event-triggered transmission. The output feedback control is calculated based on local estimates and on information received from other subsystems in the distributed system to meet the overall objectives. The design problem of the event-triggered output-feedback control is proposed as a linear matrix inequality (LMI) feasibility problem. The feasible solution of the LMIs results into a stable event-triggered output-feedback control scheme. The performance of the event-triggered control versus time-triggered control is evaluated over wireless network with extensive simulations. The simulations show that the event-triggered control results in efficient resource utilization with stable performance as compared to time triggered control. The study concludes that the event based monitoring, estimation, and control should be the first choice for distributed networked industrial systems where computational, communication and energy resources should be used efficiently.

ملخص الاطروحه

الاسم : محمد صبيح
عنوان الاطروحه : خوارزميات التحكم في النظم المتوزعة الشبكيه الصناعية
المجال الرئيسي : هندسة النظم
تاريخ الدرجة : ديسمبر ٢٠١٣

تتكون نظم التحكم المتوزعة من عده مكونات مثل الحاكم ،المجس و المحفز ، والتي بدورها تتواصل من خلال شبكة إتصالات. وقد تطور التحكم الشبكي في المصانع من خطوط إتصال مخصصة الى خطوط إتصال موزّعة في شبكه اتصال مشتركة.و بشكل عام تعتمد نظم التحكم والاتصال في نظم الشبكات الموزعة الصناعية على أخذ العينات بشكل ترددي، وهذا يؤدي الى الزيادة في اشغال شبكات الاتصال والمعالجات الحاسوبية مما يؤدي الى زيادة في تدفق البيانات في شبكة الاتصالات. وتؤدى هذه الزيادة في استخدام الشبكة الى مشاكل فى التاخير في نقل البيانات و ضياع بيانات و تجاوز أحمال الشبكة ومن ثم تؤثر على كفائة واستقرار دوائر التحكم في الشبكة.

وفى هذا الصدد تقدم هذه الاطروحه حلا علميا بالاعتماد على مبدأ الحدث للتقليل من أحمال الشبكة وتجنب تأخير وضياع البيانات.

وتتبنى الاطروحه مبدا "الحدث للتغذية المرتجعه" لمخرجات النظام فى تطبيق نظم التحكم والاتصال مستخدمه شبكات الاتصال اللاسلكية و معتمده على اساليب المحاكاة والتجربة الحوسبيه لنظم التحكم المتوزعة. ومن خلال البحث تم اقتراح أساليب علميه رياضيه لدعم استخدام التغذية المرتجعه من المخرجات لنقل عينات واتمام عملية التحكم بواسطة مبدا الحدث .و يتنبأ نظام التوقع المتوزع بقيم عناصر النظام من خلال القيم المحلية المتوفرة ويتخذ على اثرها الاجراء لنقل المعلومات استمرارا لتواصل العمليات الصناعيه وتحقيق الاهداف العامة لهذا النظام المتوزع.

وقد تم أستخدام الرياضيات العاليه فى توصيف عملية تصميم الحاكم على شكل ايجاد حلول لنظام متباينات المصفوفات الخطية و يعتمد تنفيذه على اخذ العينات للتغذية المرتجعه من المخرجات بواسطة مبدأ الحدث. وينبغى التاكيد على أن الحاكم المصمم يضمن الاتزان الديناميكى لنظم التغذيه العكسيه كما يؤدى الى كفاءة عاليه بالنسبة لوقت أخذ العينة للتحكم في شبكة الاتصال اللاسلكية.

و قد أظهرت نتائج المحاكاة أن طرائق الحوكمه المستنبطه بواسطة أخذ عينة بمبدأ الحدث كفاءة في استغلال الموارد مع المحافظة على الاتزان الديناميكى بالمقارنة مع نظم التحكم المعتمدة على أخذ العينات بشكل ترددي .و عليه أكدت هذه الدراسة في أن التحكم وادارة النظام بواسطة مبدأ الحدث يجب أن تكون الخيار الأول في نظم التحكم المتوزعة بشبكة المعلومات في التطبيقات الصناعية والتي يكون فيها استغلال موارد معالجة البيانات ونقلها والطاقة المستهلكة في ذلك في أكبر قدر من الكفاءة والتوفير.

CHAPTER 1

INTRODUCTION

1.1 Overview

During the last few decades, the fields of control, communication and computation have been closely enhanced to advanced technology horizons. The overlapping and sharing benefits of these technologies have made possible to realize smart devices of intended operation ranging from sensing, computing, control, communication, and actuation. The modular nature of devices and standard interfaces of communication have made possible to develop intelligent large scale systems. On one hand, we expect that the technology has enabled us to develop systems that are more efficient in terms of energy, performance, safety, productivity, and can obey the international standards (e.g., reduced NO_x and CO_2 emission). On the other hand, they offer challenges due to the distributed nature of the overall systems. Computation is of distributed nature and communication is through packet based data transfer. For instance, if we think of a process plant scenario, where several sensors, actuators and controllers can communication over a packet based communication network, the traditional control techniques can't be directly applied for analysis and design. Therefore, it requires to develop new tools for analysis and design specially in the aspect of distributed networked industrial system. This work focuses on the event-based methods for communication and control of the distributed networked control systems.

This research is about Distributed Networked Industrial Systems (DNIS) from event-triggered sensing and control point of view. Distributed control system (DCS) is the standard way of automation (control and instrumentation) for industrial systems specially for process control applications. All the process plants use a distributed control system (DCS) for continued and safe operation. Conventionally, the individual control loops send and receive information as either 4-20 mA or 3-15 psi signals. Technological advancement in digital devices and computer networks has shifted the information flow in control loops towards the use of digital communication buses (e.g, Foundation fieldbus). Recently, the announcement of wireless standards for automation (WirelessHART, and ISA100.11a) has opened new research opportunities and potential applications in a given distributed control system over wireless network.

This research envisions advanced industrial systems of distributed nature, where the sensors, controllers and actuators are communicating over shared communication network. Interestingly, the current practices of periodic sampling based theory faces challenges due to the asynchronous measurement, distributed nature of the plant and communication via shared networks. The distributed nature of the plant, and presence of a shared network encouraged to find the research answers in Event-triggered control theory instead of commonly used time-triggered control theory (also known as sampled data control theory). Event-triggered control scheme is chosen due to its reduced communication and computational requirements, thus making event-triggered control scheme potential choice when the system under study is distributed and control elements send and receive information over shared network via some communication protocol. The choice of ETC is made due to its inherent potential to deal with the control performance as well as the communication constraints.

Some limitations in existing results on event based methods include: (1) assumption of full state measurements and thus offer full state-feedback controllers and schemes, (2) use of centralized schemes which require access to all actuators, sensors, and controllers. Such centralized schemes are unrealistic and non-practical for a distributed networked systems. (3) Output-feedback in distributed networked event-triggered has not been addressed. From the review of related research, the following motivational points are observed:

- Event triggered control for distributed NCS is new research horizon & open for research. Existing work on event trigger is on state feedback only. Output feedback event triggered control is open for research.

- Wireless network system has not been researched for event triggered control. Specially the recent standards WirelessHART and ISA100.11a are open for

Event triggered distributed control research.

The open research area envisioned is to combine the potential of event triggered control and wireless network control for the distributed networked control systems.

1.2 Problem Statement

The research problem for this dissertation can be stated as: *"Given a distributed networked control system (DNCS), develop a design method for the event-triggered output-feedback control of the DNCS. Study and evaluate the performance of the event-triggered communication and control of the DNCS in the context of wireless sensor network."*

1.3 Objectives

The filed of distributed networked control systems is rich for research. Event based control theory for such systems expands the research horizon of control theory to new directions. Thus, event based control for distributed networked control offer a rich research field. Although the field is rich, this research will focus on following areas of Event trigger control for distributed networked systems:

- To develop theory and design methodology for Event Triggered Output Feedback for Distributed Networked Control Systems.
- To study and evaluate the performance of Event Triggered Control in the context of Wireless Sensor Network

1.4 Research Approach

To achieve the objectives of this research, following research plan is followed:

- comprehensive literature review is conducted
- simulation and experimental investigation is conducted to realize distributed networked control systems (DNCS)
- Developed event-triggered output-feedback control for DNCS
- Comparison, study and evaluation of event-triggered and time-triggered control over wireless network

1.5 Outline of the Dissertation

The remainder of the dissertation is organized as follow: the first chapter opens the discussion of the thesis topic and research objectives. A general literature review in the area of event-triggered control is presented in chapter 2. The aim of chapter 3 is to realize the control systems with networking features. Chapter 3 presents the simulation and experimental investigations for distributed networked control systems. The learning outcomes from chapter 3 put the foundation for the study of networked systems. In chapter 4, design theory for event-triggered output-feedback control for distributed networked control systems is presented. Chapter 5 presents the simulation study and evaluation of event-triggered control versus time-triggered control over wireless communication networks. The closing chapter 6, provides conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Event-Triggered Control

Formally, the control theory started around 1869 when physicist John Clark Maxwell did dynamic analysis of the centrifugal governer [1]. Since then, control theory has taken several interesting research horizons due to analytical and technological developments. From timing aspect, the control theory has gone through continuous time theory and discrete time theory. The control framework is also expended from dedicated single loop control to distributed plant control environment, i.e., from embedded systems to large scale systems. The latest technological revolution impacting and reshaping control theory is the information sharing capabilities over shared networks. This capability has encouraged and helped to realize the field of distributed networked control systems, in other words, coordinated distributed control systems.

In fact, over the recent years, distributed and intelligent systems closed over communication network has become a fruitful area for experimental and theoretical investigations. Different research areas for such systems have expanded including intelligent-optimum manufacturing systems, energy-saving building, smart power grid, networked water-oil resources, social-academic networks, cyber-physical systems, reconfigurable systems and financial engineering to name few. Such propagating research interest to different fields carries diverse reasons. The reasons include: technological advances that has enabled information acquisition of distributed and large-scale networked systems, utilization of different structures, diverse modeling techniques like graph theory [2] and impulsive modeling from hybrid systems [3], and improved computing and communicating devices with common protocols [4].

Moreover, the growing research on event-triggered control, estimation and optimization has created an awareness of the need for the development of new modeling and control methods. In parallel, it is also necessary to develop corresponding analytical, computational, and communication methods.

For linear systems, sampled-data control theory provides powerful tools for direct digital design, while implementations of nonlinear control designs tend to rely on discretization combined with fast periodic sampling. In recent years, there has been a growing research interest in event-based control, in particular in connection to distributed and networked control systems. The basic idea is to communicate, compute, or control only when something significant has occurred in the system. The motivating factors for event-triggered control may also include constraints on system resources.

Now the approach in control theory is to take into account the communication issues in the formal analysis and design. In addition to this, Event triggered has been highlighted as the potential and appropriate candidate for the control of distributed networked systems. Event-triggered methods have capability to reduce the network traffic, and computational load, while providing the similar performance as time-triggered equivalent. The filed of Networked control system (NCS) has got extensive research attention during last decade, e.g., [5] [6] [7] [8] [9], and little work on the event triggered NCS, e.g., [10], and [11]. The aim of this chapter is to explore the research on event-triggered control system and its application to distributed networked and wireless based systems.

A distributed networked control system (NCS) consists of numerous coupled subsystems (also called agents), which are geographically distributed. In such a system, individual subsystems exchange information over a communication network. These networked systems are found throughout any national infrastructure with specific examples being the electrical power grid and transportation networks, air conditioning and alarm systems for large scale systems. In the phrase "distributed networked control system", network refers to the communication infrastructure supporting feedback control (cyber space), while the term distributed refers to the fact that individual subsystems are physically interconnected in a way that can be modelled as a network (physical space). DNCS is a class of cyber-physical systems. The networking of control effort can be advantageous in terms of lower system costs due to streamlined installation and maintenance costs.

The introduction of a communication network, however, raises important issues regarding the impact that such communication has on the control systems performance. In practice, communication, especially wireless communication, takes place over digital networks where the data is transmitted in discrete packets. These packets may be lost during communication. Moreover, the communication media is a resource that is usually accessed in a mutually exclusive manner by neighborhood agents. This means that the throughput capacity of such networks is limited. So one important issue in the implementation of such systems is to identify methods that more effectively use the limited network bandwidth available for transmitting state information.

For this reason, some researchers began investigating the timing issue in NCS in terms of message scheduling. In other words, how frequently should subsystems communicate to ensure that the NCS has a desired level of performance. Usually, the controller is designed with the assumption of perfect communication and then a bound is determined for the maximum allowable transfer interval (MATI) between two subsequent message transmissions to ensure closed-loop stability.

Established control theory and textbooks assume periodic nature of sampling and control to design and implement feedback control systems (e.g., [12] and [13]). The alternate approach to periodic control is aperiodic control systems.

The debate and research on periodic vs. aperiodic has recently got popularity in the research community of control theory due to technological developments and frequent use computers and communication systems.

Fundamental reasons of resurgence of event based control include:

- Increased use of shared networks (both wired and wireless) in monitoring and control applications, which has raised importance of efficient usage of computation, energy and communication resources. Thus, now control systems should be designed with additional constraints in mind, which are, energy constraints, computational constraints, and communication constraints.
- Initial work by Astrom [14] and Arzen [15] has shown advantages of using event based control. This has lead further systematic developments like [16], [17], [18], and [19].
- Desire of using networked control systems over shared communication medium specially using wireless communication.

Elements of Event based control system consists of: (1) Feedback Controller, and (2) Triggering Mechanism.

Types of ETC

ETC purely based on hardware (or physical) event is considered of Reactive-ETC, while ETC with software (i.e., involved with estimation) is treated as Proactive-ETC [20]. ETC can also be categorized into: (1) State-Feedback ETC, and (2)

Output-Feedback ETC, depending upon the availability of system states for measurement and feedback. Packet loss in the communication system can be modeled as either independent identically distributed (IID), or as Markov Chains. With all different aspects and directions of research, the literature on ETC is rapidly increasing. Still the theory of ETC is not matured ([2], [20]). Besides the simulation and quite few experimental results, the deployment is rare. The next major milestones and responsibility for the research community is to provide theoretical results and experimental validations in Event-Triggered Control.

From current insurgence of literature on event based control, we can define the following types of event based control:

Event-Triggered Control

A triggering condition based on current measurements is continuously monitored, when the condition is satisfied, event is triggered. Event-triggered control is reactive and generates sensor sampling and control actuation when, for instance, the plant state deviates more than a certain threshold from a desired value. Depending upon the full or partial availability of states for measurement and control, the event based control system can be further categorized as:

- State-feedback ETC
- Output-feedback ETC

The output-feedback ETC can be designed as (1) observer based, or (2) direct output based.

Self-Triggered Control

The next update time is pre-computed at control update time based on prediction using previously received data and knowledge of the plant dynamics. Self-triggered control is proactive and computes the next sampling or actuation instance ahead of time [20]. Thus, design of an event based control system consists of two key elements: (1) design of feedback controller, and (2) design of triggering condition.

Periodic Event-Triggered Control

This scheme is presented in [21] to keep a balance between periodic sampled data control and event triggered control. In this, condition that triggers the event is of periodic nature, while keeping the reduced resource utilization.

2.1.1 Problems and Challenges in Event-Triggered Control

Fundamentally, Event based control is based on Lebesgue sampling [22]. Analytical development of event based strategies face challenges due to Lebesgue sampling which is non-periodic, non-Gaussian and non-linear. This sampling is a function of event, and the occurrence of event may be stochastic in nature. Therefore, generally, ETC should be considered and treated as of nonlinear, and hybrid nature in general framework. Key bottlenecks that encourage the use of

ETC may include: (1) limitations on computational processing power, (2) sensor quantization, (3) cost per actuation, (4) cost of communication of signals, and (5) synchronization issue between subsystems.

2.2 Wireless Communication in Industrial Systems

Currently, there are two standards for industrial wireless automation applications: WirelessHART and ISA100.11a. Both industrial standards are based on the IEEE 802.15.4 radio [23]. The IEEE 802.15.4 standard is suitable for building automation [24], industrial monitoring, and control applications [25], [26]. The main characteristics are low bit rate and low power consumption. The WirelessHART standard and some implementation details are discussed in [27]. ISA100.11a is in practice very similar to WirelessHART, as both have similar design goals and use the same radio, but the two standards are not compatible. The WISA system is a complete solution for a reliable wireless cell in industrial manufacturing [28].

The architecture of both industrial wireless network standards include sensor nodes, wireless routers communicating with each other, and a gateway, which is connected to the automation Fieldbus and the rest of the automation system. Mesh networking is possible for reliability, but all communication between devices in the wireless network is routed via the gateway. This routing constraint makes the network scheduling and routing design easier.

WirelessHART was approved by the International Electrotechnical Commission (IEC) as a full international standard (IEC 62591Ed. 1.0) in March 2010. Several manufacturers have released devices for WirelessHART and it is by now in use in control applications [29]. The ISA100.11a standard [30] was published in September 2009, gained IEC approval in 2010. Hence, the field of industrial wireless control has taken its first steps. The standards are designed for determinism, such that traditional control can readily be applied. Although deterWirelessHART was approved by the International Electrotechnical Commission (IEC) as a full international standard (IEC 62591Ed. 1.0) in March 2010. Several manufacturers have released devices for WirelessHART and it is by now in use in control applications [29]. The ISA100.11a standard [30] was published in September 2009, gained IEC approval in 2010. Hence, the field of industrial wireless control has taken its first steps. The standards are designed for determinism, such that traditional control can readily be applied. Although determinism is the main design goal, this is never fully assured and is on the expense on performance and flexibility.

WirelessHART uses a combination of time division multiple access (TDMA) and frequency division multiple access (FDMA) MAC protocol. The TDMA slot is 10 ms, in which the data packet with sensor or control information and an acknowledgement are exchanged between two nodes. The network and transport layers are based on the Time Synchronized Mesh Protocol (TSMP) originally developed by Dust Networks [31]. Each node pair is assigned a unique time/frequency slot for contention free communication by a centralized network manager [31]. Some slots can be reserved for contention based access using CSMA, for communicating rare event messages or retransmissions in case of dropped packets. Additionally, frequency hopping is used to mitigate interference on some channels. A more detailed presentation of WirelessHART can be found in [27]. The benefits of WirelessHART and how to accommodate the control system to the wireless network, and meet the required control performance, are discussed in [32]. ISA100.11a uses similar techniques and both network standards can be applied where the application can tolerate a delay jitter in the order of 100 ms. The delay jitter stems from packet drop due to interference.

The scheduling and routing of the WirelessHART and ISA100.11a networks are left open in their standards. Due to the determinism of the TDMA approach with a pre-determined schedule, fixed bounds on the communication can be advertised, although not guaranteed. In the case of packet drops, retransmission is needed, which may cause the information to exceed the delay bound. Retransmission slots must thus be incorporated into the schedule, which reduces the bandwidth usage and unavoidably introduces delay jitter. Retransmission can take place on the slots allocated for random access, or on extra slots allocated in the schedule. The schedule and retransmissions determine when information is available to the control system, and hence affect the control operation. There exists work where the actual network MAC protocol and related functions such as duty-cycle [33], or routing and schedule [34], [35] are taken into account in the control stability proof.

The current standards are designed for reliability and are thus conservative, which implies that closed-loop control of fast processes is not possible. The design decisions of both standards ensure a relatively simple network design. The use of TDMA ensures determinism (disregarding packet drop due to interference) and the routing via gateway constraint results in a simpler routing design. Current research related to the standards is for instance the optimality of the time/frequency-slot scheduling and routing [35]. The room for improvement is thus limited.

The research issues therefore include new technologies and algorithms to advance the capabilities of wireless control. The introduction of new agile and intelligent communication methods will improve the field. These new networks will probably not guarantee a certain QoS or be deterministic, such as the case when using TDMA. One research direction is then the introduction of adaptive control methods to compensate for the deficiencies of the wireless communication, which this thesis focuses on.

In the future, wireless control systems with low performance requirements are likely to emerge. These can be based on commercial off-the-shelf hardware (COTS), by adopting robust control algorithms. Today's COTS hardware, such as WLAN, Bluetooth, and IEEE 802.15.4, utilizes mostly CSMA type communications [36]. This implies that the network is inherently non-deterministic and unreliable. There are no quality of service guarantees, such as designated transmission slots. This does not mean that wireless applications on this hardware are impossible; it is rather a research opportunity. Several practical applications can be proven to work satisfactorily, using simulations and pilot implementation.

2.3 Applications of Event-Triggered Control

Wireless based Systems

Advancement in Wireless technology has motivated control researchers to study the control over wireless channels due to its many benefits. Key benefits of a wireless device, (sensor, actuator or controller from a control engineer's aspect), include installation at difficult places, mobile operation, reconfigurability, multi-path (like mesh) networks , no installation of wires, etc. Wireless based solutions are studied and offered with different names like Wireless Automation, Wireless Sensor/Actuator Networks, and Wireless Sensor Networks for monitoring and control applications. The future is undoubtedly in favor of wireless based solutions.

The shared communication channels (i.e., open air medium), battery operated wireless nodes, and low computational power at nodes, offer challenging sensing and control schemes for wireless control systems. Such constraints on resources encourage and make Event based techniques, natural choice of operation in wireless control systems. Therefore, in this section, recent literature on event triggered control for wireless systems is presented.

In [37] a decentralized scheme for event triggered control over wireless sensor/actuator network (WSAN) with low computational requirement is presented. Commonly the wireless channel is used for monitoring applications, while the aim is to use wireless actuators to close the feedback loop over wireless [37]. By using event triggering in wireless, the number of control computations, and sensor transmission are reduced. This leads to energy efficient control loops with satisfactory performance. Compared to [38], where a method is proposed for distributed event-triggered control for weakly coupled subsystems, approach in [37] does not require weakly coupled subsystems. The decentralized technique is tested on a four-tank system. This work can be further extended to general dynamic controller in event triggered implementation and to design adaptation rules for flexible implementation.

Output feedback in event triggered control has been studied by few researchers only. For example, in [39], the output feedback of wireless networked control systems is studied. The communication links, between sensor to controller and from controller to actuator, are treated separately. Based on assumption of weakly coupled subsystems, the triggering depends on local information. This way, the sensor and controller's event-triggeres are not required to be synchronized. A good discussion on event based sampling over wireless networks can be found in [40]. As first step to develop theory for event based control, classical control techniques like PID and minimum variance control are extended to event triggered control, for example, [22], [15] and [40]. In such extensions, an additional activity includes the design of event detector for the best aperiodic sampling.

In [41], wireless based event triggered control has been investigated on an experimental setup. The work in [41] investigated an event triggered design and

implementation for a nonlinear 3D tower crane. An Event-Generation Circuit (EGC) is also demonstrated to flexibly implement event-driven controllers in networked systems. Two fold benefits of event triggering for wireless include extended lifetime of sensor nodes and reduced network traffic. Performance studies are also presented in [41] of the event triggered control and the time triggered control in presence of disturbance, delay and packet loss. Although resulting event triggered method shows similar performance performance with much reduced communication, it does not provide guarantee of stability. There can be several interesting future extensions to the research presented in [41], including general reference tracking, conditions on stability, and decentralized event-triggered control. A co-design approach is proposed in [42] to modify the IEEE 802.15.4 MAC standard to implement event-triggered control over wireless sensor and actuator networks. Based on [42], the problems in event triggered wireless control can be stated as : (1) Find triggering condition for sensor and controller ensuring stability and desired performance while minimizing the energy utilization at wireless nodes.
(2) Design and implement the event based sensing and control strategy using off-the-shelf technology with satisfactory performance and stable control loops.

In [43], an event-based technique for distributed estimation over wireless sensor networks (WNSs) is studied. Local Luenberger based observers are used with a consensus strategy for distributed estimation. The observer is designed in time triggered scenario using linear matrix inequalities, then an eventbased strategy is proposed to reduce communication and energy consumption of the nodes. The work in [43] does not consider packet loss and delay, thus a natural extension will be investigation of packet dropouts and time delays. Further, [43] can be extended for more general distributed observers and distributed controllers for wireless based event triggered framework.

Event-Based Control for Wireless Automation: It has been envisioned that Event-based control can help to implement and use wireless networked control systems. The aim is to achieve efficient use of network resources while fulfilling the required control objectives. Stochastic control approach is natural to be investigated because of the probabilistic nature of wireless channel. Research on wireless based event triggered control will lead to new research questions including multi-loop systems and multi-hop networks. What industry will like is investigation of control techniques over mesh-wireless networks.

Event-Triggered Control for Distributed Systems

Since, the work on event triggered control is recently started, most of the work on event triggered and networked control is focused on single control loop. But, some researchers have started to investigate this new control strategy for multiple feedback loops in the presence of physically distributed sensors and actuators.

Distributed algebraic connectivity estimation for adaptive event-triggered consensus is presented in [44]. In several multi agent control problems, the convergence properties and speed of the system depend on the algebraic connectivity of the graph. A particular event-triggered consensus scenario is discussed in [44], and show that the availability of an estimate of the algebraic connectivity could be used for adapting the behavior of the average consensus algorithm.

A novel distributed algorithm for estimating the algebraic connectivity is presented, that relies on the distributed computation of the powers of matrices. It also provides proofs of convergence, convergence rate, and upper and lower bounds at each iteration of the estimated algebraic connectivity. The work in [44], can be combined with higher level algorithms for adaptive consensus in a parallel fashion, by taking advantage of our upper- and lower bound estimates of the algebraic connectivity.

In [45] a distributed event-triggered control for multi-agent systems is discussed. Event-driven strategies for multi-agent systems are motivated by the future use of embedded microprocessors with limited resources that will gather information and actuate the individual agent controller updates. The controller updates considered here are event-driven, depending on the ratio of a certain measurement error with respect to the norm of a function of the state, and are applied to a first order agreement problem. A centralized formulation is considered first and then its distributed counterpart, in which agents require knowledge only of their neighbors states for the controller implementation. The results are then extended to a self-triggered setup, where each agent computes its next update time at the previous one, without having to keep track of the state error that triggers the actuation between two consecutive update instants. The work in [45] can be extended to the performance analysis of the framework and its application to other cooperative multi-agent control tasks.

Since in [45], reduction of control update is emphasized, a natural extension of [45] is to investigate sensing limitations. Recently, event based methods are also studied for advanced control techniques, for example, in [46] event-based model predictive control for the cooperation of distributed agents is investigated. [46] presented an event-based framework for the control of a team of dynamically coupled distributed agents. These agents are controlled locally by Nonlinear Model Predictive Controllers (NMPC). The optimal solution is sought for MPC only at event triggers.

Distributed event-based control strategy for a networked dynamical system is studied in [47] linear interconnected systems. Triggering rules of subsystems to broadcast are based on local information only. Convergence properties and lower bound on broadcasting period is provided. The number of events are reduced by using a model based approach.

The framework of [47] is extended to network delays and packet losses in [48]. To deal with the network issues on delay and packet loss, two communication protocols are proposed to ensure the stability of the linear distributed system. These protocols preserve a bounded stability near to a small region around the origin. Such bounds on delay and packet losses are derived analytical for the two proposed communication protocols.

Distributed event-triggered tracking control of leader-follower multi-agent systems with communication delays is investigated in [49]. Key motivation of event based approaches for distributed system is due to the usage of embedded processors in distributed systems where energy and computational resources are limited or at least not abundant. The stability of the tracking control multi-agent system is ensured by an ISS Lyapunov function.

In [50] function block automation standards, i.e., IEC 61499 and IEEE 1588 are investigated for time-complemented event-driven distributed control. Initial study is provided for the applications of IEC 61499 Function Block standard in distributed motion control systems, where synchronization is of crucial importance. In particular, an investigation on the possibilities of applying event-driven function blocks in the time-based motion control system has been performed on the SIDEL SL90 packaging machines control system.

In [51], distributed event-triggered sampling scheme for controlling interconnected systems is presented. The individual subsystems in the interconnection decide the triggering independent to other subsystems. Such decision is based only on the subsystem's state and a Lyapunov function. Stability condition of the overall system is developed on small-gain theorem.

Event-triggered and self-triggered stabilizing control is studied in [52]. The framework of [53] which is developed for sampled-data systems is extended in [52] to develop event-triggering rules for distributed networked control systems. The self-triggering conditions are derived by applying the techniques of [54]. A fundamental question in distributed networked control is : *Given a set of physically distributed sensors and actuators, how should communication between the different nodes be scheduled*? [52] The distributed framework of [52] can be extended to design communication protocols for event triggering conditions on information sharing between distributed nodes. Distributed Network Utility Maximization (NUM) using Event-triggered Barrier Methods is investigated in [55].

In [11] event-triggered data transmission in distributed networked control systems with packet loss and transmission delays is investigated. In this distributed event-triggering scheme, a subsystem broadcasts its state information only when the local state error exceeds a threshold value. For nonlinear subsystems, the local event design is transformed into local ISS design problems; for linear subsystems, the design is simplified to be local linear matrix inequality (LMI) feasibility problems. With the assumption that the transmission delay is zero and the number of each agents successive data dropouts is less than its MANSD, the resulting NCS is shown as finite-gain $\mathcal{L}_p$ stable. When the transmission delay is not zero, state-based deadlines are provided that are always greater than a positive constant. As long as the delay in each transmission is less than the associated deadline, the resulting NCS is asymptotically stable, provided the external disturbance vanishes.

In [56] event-triggered broadcasting across Distributed Networked Control Systems is studied in presence of wireless communication networks. Broadcasts are decentralized and based on the individual subsystem's measured states. Information from the neighborhood is used to adjust the event-triggering level. This way, a subsystem can adjust its broadcast rate in view of the amount of activity in its immediate neighborhood. The work in [56] is further extended in [38] with investigation of distributed networked systems in case of data dropouts and transmission delays.

Distributed optimization in event triggered framework is investigated in [57] for sensor networks. An event-triggered distributed algorithm is proposed for the data gathering problem and the convergence is discussed. It is shown that the algorithm reduced the number of message exchanges as compared to the alternate dual decomposition algorithms.

Distributed event-triggered estimation over wireless sensor networks is also studied in [58]. This estimation algorithm performs distributed estimation of networked systems when sensor measurements are transmitted over a wireless sensor network.

Passivity-based I/O approach for stabilization of large scale networked control systems (NCSs) with event-driven communication is studied in [59]. A cellular model is used to represent the large scale NCSs and it is assumed that each subsystem is an output feedback passive (OFP) system. Here also, the communication strategy of broadcasting information depends on local output error against a threshold. Finite-gain L2 stability is analyzed in the presence of bounded external disturbances.

2.4 Research Trends

As research hypothesis of utilizing ETC for control applications is blooming, there is a need of pure scientific methods to properly deliver theorems, and experimental validations. Interesting, ETC not only focus on better control, but also to optimize the resources (i.e., communication and computational).

Several contributions have been presented by different researchers, but all agree to indicate the need of development of mature system theories for event-triggered networked systems. Such theories are needed for the deployment of ETC over networks in large variety of practical control applications. Besides the enhanced flexibility and maintainability, networked control architectures allows the control systems to have less wiring, and as the ideal case being completely wireless. In some cases, wiring is impossible, such as multiple vehicle scenario. So, the trend is now, to develop control strategies with communication networks in consideration. In future, communication will be an integrated part of the control system design.

Theoretical Results: One possible next step, that is certainly needed, is to develop the necessary system theoretic results underlying complete and efficient (co-)design methodologies for event-triggered and self-triggered control. This should enhance the usage of these control strategies in practical applications.

Practical Validation: In fact, their validation in practice is an important next step (which will undoubtedly raise new theoretical questions). Indeed, even though many simulation and experimental results show that event-triggered and self-triggered control strategies are capable of reducing the number of control task executions, while retaining a satisfactory closed-loop performance, see, [60], [61] , [62], [14], [15], [63], [64], [65], [66], [67], the actual deployment of these novel control paradigms in relevant applications is still rather marginal.

Quantitative Assessment and Comparison: A possible stimulus for changing this situation, being a third important step, is to demonstrate quantitatively how and when event-triggered and self-triggered control outperform the classical periodic sampled-data control approach. The quantitative evaluation of all these strategies should reflect both control costs such as quadratic costs as in LQR control or relevant Lp-gains, and communication costs such as average sampling rates, minimal inter-event times, or transmission power. Fair assessments and comparisons are needed helping the practitioners to identify the situations in which these aperiodic control strategies offer benefits that can not be guaranteed by the conventional periodic paradigm.

Event-Triggered Adaptive Control in Wireless Control Systems: In recent years, the standardization of digital wireless communication and protocols suitable for automation and control, such as ZigBee, WirelessHART and ISA100 has started the field of wireless automation. The topic of wireless automation has been taken seriously by the industry as well as welcomed by the research community due to its inherent potential. This helps us to envision the future of current fieldbus based automation system to wireless based automation systems. Recently, algorithms and simulation environment have been developed for future agile wireless control systems in [68]. Once the wireless control system is stable or the application in non-critical, nothing can prevent the used of cheap wireless control to be used in near future for the plant operation. Wireless control systems can exists parallel with the special deterministic industrial networks and protocols for critical and unstable control loops. The development of industrial communication networks from fieldbus to wireless has been discussed in [69]. Research on wireless control networks and their applications have been comprehensively discussed in [70] and [71]. In the current wireless automation scenario, the wireless typically operate in the open ISM frequency band. This ISM band is also used by the office networks (i.e., WirelessLAN) and Bluetooth devices, and thus ISM is crowded now. Future applications require that a separate frequency band should be reserved for wireless automation application to have interference free wireless operation for monitoring and control applications. The future research issues include development of new frameworks and algorithms to advance the capabilities of wireless control. Currently, research on wireless control system is primarily for time-triggered (i.e., periodic) systems, e.g., [68] and [72]. A needed research direction is to study the event-triggered control for wireless control systems assuming non-deterministic communication protocol. Event-triggered control has potential to realize more agile and resource optimized control methods than time-triggered control.

Reference Tracking: As recommended in [73], development of event-triggered control theory for reference tracking is a good future research. As event-driven control is a widely open and a barely explored field of research, many new applications can be considered that have great potentials for both industry and academia. The importance of this field is more and more recognized by industry, as they have to produce more complex systems for decreasing cost prices. This involves hard multi-disciplinary designs for which one cannot design controllers that only focus on the control performance, while posing hard demands on other systems aspects, like software implementation and sensor specifications.

Sensor-based event-driven control: [73] studied a typical design of an event-driven controller implementation in the spatial domain. To be applicable in a much broader range of applications, more research has to be carried out for designing controllers in the spatial domain. An interesting question arises whether or not there are applications in which spatial models are more natural than models with time as the independent variable. E.g. some of the disturbances in the printer are typically position dependent. One important area that automatically emerges is spatial identification. An interesting topic is how identification could be carried out by using low resolution sensors. Furthermore, it would be interesting to research how the spatial analysis could be incorporated in the design of other controller types, like H1, LQG and MPC.

Efficient Event-driven control to reduce resource utilization: [73] analyzes a particular event-driven control structure, it already indicates the complexity and challenge for the analysis and synthesis of these type of control loops for which the controller triggering cannot be considered synchronous in another domain. This work provides a first step towards a proper analysis of these types of control loops. Moreover, to be applicable in industry, methods are required that can be applied to analyze control loops within minutes, as industry has to develop high-tech systems in very limited time spans. Given the advantages of event-driven controllers and the various sources of event-triggering mechanisms present in industrial practice, it is fruitful to continue this line of research and to develop a mature event-based system theory.

Robustness of event-triggered NCS: The work on event-triggered on asymptotic stability has been presented in [74], but robustness has not been studied. Study of robustness for event-triggered networked system is a promising future research question.

Impact of quantization: The study of the impact of quantization on event-triggered NCS is also a good research question for future studies. Inclusion of quantization effects of the sensors on the stability and performance of the control loop [75] and [74].

Dynamic deadlines: The deadlines for the delays may be conservative because they are selected before the system is deployed. The behavior should be ensured over a range of possible input disturbances to the system. Therefore, the use of dynamic deadlines that are computed based on the previous sampled information will reduce the conservativeness of the deadlines of the bounds. Thus, a future work can be carried to extend the work in [74] for dynamic deadlines.

Self-triggered over wireless sensor-actuator networks: It would be interesting to study the self-triggered control over wireless sensor-actuator networks, which is initiated in [76], [8], [77], [78], and [38].

Large delays: Most of the current work like [75] on stability restricts the delays to be smaller than the transmission interval. The future work requires study the cases when delays are not restricted to be smaller than the transmission interval.

Theory of event-triggered control systems: Major contributions in the field of event-triggered control are based on experimental and simulation studies, and a comprehensive system theory for ETC is currently not available. Therefore, several recommendations for future research are given below that will contribute to a comprehensive system theory for ETC that will support the deployment of ETC in a large variety of control applications.

Reducing conservatism in the analysis: The illustrative examples in [75] have shown that the upper bound on the magnitude of the ultimate bounds and the L1-gain, based on the theory, were larger than what was expected from the simulations, and the lower bounds on the inter-event times, again based on the theory, were smaller than the inter-event times observed in the simulations. Furthermore, the theoretical upper bounds on the L2-gain in the illustrative examples in [75] were larger than what could be concluded from the simulations. Therefore, future work on (P)ETC should focus on improving the upper bound on the magnitude of the ultimate bound, the upper bound on the L1-gain or L2-gain, and the lower bound on the inter-event times to become closer to the true value of the ultimate bound, the L1-gain, the L2-gain and the minimum inter-event times, respectively.

Including network-induced artifacts: The fact that ETC aims at saving communication resources, makes it a very useful control strategy to be implemented over a multipurpose communication network. Hence, ETC provides an alternative to the conventional sampled-data controller used in the NCS literature. However, in the case that ETC is used in the context of NCSs, the control system again becomes subject to time-varying transmission delays, packet dropouts and perhaps even communication constraints, and the robustness of the ETC algorithm against these phenomena has to be quantified. In the case of PETC, the control system might also become subject to time-varying transmission intervals, as the local clocks might not be synchronised exactly, and the the robustness of the PETC algorithm against time-varying transmission intervals has to be quantified as well. Therefore, future work could focus on extending the framework presented in [75] to include the case where the ETC system is subject to the network-induced phenomena studied in the first part of this thesis. In fact, the theory developed in the first part of the thesis can provide a good starting point to achieve this. Once this task is accomplished successfully, ETC might be the natural control strategy for many NCS applications.

Solving the controller and ETM co-design problem: The co-design problem has been addressed partially in the literature for event-triggered control. Namely, the minimum attention control problem solved in [75] focusses on state-feedback controllers and yields a self-triggered control algorithm, thereby providing only a solution to very particular co-design problem in ETC. Furthermore, the solution of the control problem has the form of an online optimisation problem. Even though these linear programs can be solved efficiently using existing solvers, the computations are numerically more demanding than, for instance, a conventional state-feedback control algorithm, which might not be desirable from an implementation point of view. If instead the optimisation problem can be solved explicitly, e.g., using multiparametric linear programming as has been done in explicit model predictive control (MPC) in [79], this computational burden might be alleviated. Therefore, future research on minimum attention control and anytime attention control could focus on obtaining explicit solutions to the optimisation problem and on formulating the problem for the case in which not all the states can be measured directly. It is important to explore ETCSs, that will support the deployment in a large variety of practical control applications, such as chemical plants, water distribution networks, distributed power generation systems, unmanned aerial vehicles, vehicle platoons on motorways, tele-operated haptic systems, and so on. In particular, ETC can have an enormous potential to revolutionise the control field as it advocates the abandonment of the conventional periodic time-triggered feedback control paradigm. The benefits of ETC being that it naturally results in less communication and, thereby, in less delay and fewer packet dropouts makes this control strategy very well suited for NCSs. The topic of NCS and ETC are treated separately in [75]. Combining these individual research of NCS and ETC will lead to interesting investigation for networked ETC to be used in future applications.

Lebesgue Sampling for MIMO Systems: Lebesgue sampling is the heart of event-triggered control. Current work on developing theorems and design frameworks for Lebesgue sampling are focused on Single Input Single Output (SISO) models, such as [80]. The future work is required to study the Lebesgue sampling for Multiple Inputs Multiple Outputs (MIMO) and higher order models. This direction is encouraged by the fact that real-time control systems may have multiple Lebesgue measurements available (such as asynchronous measurements).

Development of Lyapunov theory for Lebesgue sampling: In the research on Lebesgue sampling, it is assumed that the signal between the Lebesgue sampling intervals is random instead of a Lebesgue integral function. It is recommended that to obtain more accurate results, the use of Lebesgue integral function in the context of Lypunov theory should be explored in future studies.

Event-Triggered Model Predictive Control: The work over robust Lebesgue control systems in [80] relies on empirical results. This indicates a need of rigorous analytical solution for robust methods including Model Predictive Control approach further leading to nonlinear systems framework.

2.5 Conclusion

This chapter provided a comprehensive overview of the latest research interest in event based control techniques. It provides an introduction to the field of event based control and highlights the current and future directions of research in this field. Specifically, the emphasis is given to the research challenges, applications to distributed and wireless automation, and possible research topics. This chapter provided a collection of important research topics in one place.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS FOR DISTRIBUTED NETWORKED CONTROL SYSTEMS

3.1 Introduction

Networked control system has been a hotspot in the research fields of control theory and control engineering applications at home and abroad. Due to major advancements in the area of networking over the past decade, a new paradigm of control systems has emerged, namely Networked Control Systems. Such systems differ from classical control systems in that their control loops are closed around communication networks. Simulation and experimental setups play vital role in the analysis and design of improved methods in control systems.

Distributed networked control systems offer challenging problems due to the communication in feedback loop. These problems are related to packet-rate, asynchronous sampling, random network delay, packet drop, bit-rate and quantization in addition to the structural complexity of decentralized system and its largeness. This requires a comprehensive need of simulation tools and experimental setups to conduct research in the area of distributed networked control systems (DNCS). The aim of this research is to study and conduct simulations and experiments for advanced research in the field of DNCS. Highlights of the topics to be explored include distributed control systems with communication. Aim is to achieve best balance between the industrial and academic approach to the topic. Several elements from state of the art plant environment like PLC, DCS and SCADA systems in view of topic will be explored. Several of the industrial communication networks like actuator sensor-interface, HART Protocol, Foundation FieldBus, Profibus etc, will also be explored. Academic research with emphasis on experimental and simulation setups in the field of distributed networked control system will be explored.

The *TrueTime* toolbox in the MATLAB environment provided very good platform for the research of networked control system, and the dynamic process of distributed real-time control system, control task execution and co-simulation environment of network interaction can be built by *TrueTime* toolbox.

The advantages provided by wireless technology are several. First, it permits to carry the capability of wired networks to areas that cables cannot reach. Considering industrial plants, wireless technologies can significantly facilitate deployment and reconfiguration by eliminating the need for installing and maintaining cabling, reducing both cost and time. However, the lack of maturity, real-time performance issues and the less reliability as compared to the wired networks, wireless technologies are not chosen for in industrial environments. Since the field of distributed systems with communication networks is evolving, setting up the appropriate simulation environment and experimental setups are required key tools for research in distributed networked control systems.

Distributed systems are composed of individual units or small systems. The smaller systems are connected with each other and thus form a system-of-systems (SoS). In [81], networked control system has been raised as a control paradigm as a part of SoS. Main challenge raised in the Sytem-of-Systems based on networked control is to achieve a SoS distributed control system that can perform robust operation against communication issues like packet losses and delay. Communication networks like TCP/IP based Ethernet is an example of connecting IP based systems to a more complex system. Investigated experiment is based on the Ethernet as an example unit for the motivation of future studies for more complex distributed systems connected over Ethernet. Moreover, the simulation package explored is capable for simulating network nodes in Matlab giving opportunity for more complex system to study. The experimental setup presented in this work is an example of a single system in SoS where more systems can be connected on the network layer.

The objectives of the research work in this chapter are:

- To review simulation and experimental setups for distributed and networked control systems
- To conduct simulations for networked control systems
- To establish experimental setup for networked control systems

Our ultimate aim is to provide a technical description on distributed-networked-simulation and experimental setup to support the analysis and control research in distributed networked control systems. In addition, we seek to cover the knowledge of simulation and experimental tools and methods of advanced research in distributed networked control systems.

3.2 Related Work

A MATLAB/Simulink-based event-based simulator for real-time control systems termed (*TrueTime*) was developed in [82]. In effect, *TrueTime*, as a co-design package, makes it possible to simulate the temporal (true) behavior of multi-tasking real-time kernels including controller tasks and to critically examine the effects of central processing unit (CPU) and network scheduling on the performance of dynamic control systems. Basically, the simulated real-time kernel can handle external interrupts as well as fine-grained details including context switches. One of the basic features of the simulator is that arbitrary scheduling policies may be defined, and the control tasks may be implemented using **C**-functions, **M**-functions, or Simulink block diagrams. The recent applications of distributed mobile agents and wireless sensor/actuator networks have called for co-simulation as a necessary tool during system development. In [83], a simulation environment for mobile wireless networked embedded systems that facilitates simulation of computer architecture (nodes) and communication networks interacting with the continuous-time dynamics of the real world was presented. Basic features of the simulator include interrupt handling, task scheduling, wired and wireless communication, local clocks, dynamic voltage scaling, and battery-driven operation. The modeling and implementation of the IEEE 802.11b standard for wireless communication within the TrueTime framework were provided. An effort describing simulation of wireless control using the WirelessHart standard was given in [84]. The impact of clock-drift on predictive controller performance where no synchronization exist between the controller and the wireless network was investigated. The simulations were done using an extension of the Simulink package *TrueTime.*

Two MATLAB-based tools, *Jitterbug* and *TrueTime*, for the analysis and simulation of how the process of timing affects control performance were described in [85]. Jitterbug simulation environment uses two types of models: (1) signal model, and (2) timing model. On one hand, *Jitterbug* was used to determine the sensitivity of a control system against slow sampling, delay, and jitter in a quick way. On the other hand, *TrueTime* was preferred for more detailed analysis from overall system perspectives, where the modeling targeted at combination of computational nodes and network blocks along with describing any dynamical system. In this way, a complete networked control system environment was prepared.

Connecting a spatially distributed system with sensors, actuators, and controllers as a networked control scheme (NCS) by a shared data network can reduce the wiring and cost remarkably. Excellent results incurred when NCS was utilized in remote operation of linear systems. However, the presence of nonlinearities was considered the major barrier in implementing a NCS. In [86], with focus on the control of induction motors, a sliding mode flux observer was used to linearize the induction motor model, such that the application of NCS became feasible. A fuzzy logic speed controller with state predictor was developed to adapt various network conditions due to the variable quality of service (QoS). Simulations were conducted by employing *TrueTime* toolbox to demonstrate the effectiveness of the adaptive fuzzy logic PI speed controller.

In [87], a network-based cascade control system on a real laboratory pilot plant using two alternative fieldbus (FB) and NCS control approaches was designed and implemented. The proposed network platform was designed so that a Smar foundation fieldbus controller (DFI-302) could be linked to a remote Siemens programmable logic controller (S7- 315-2DP) through an industrial Ethernet. The networked-based configuration was maintained operational using the Smar OPC Tag browser and Siemens WinCC OPC C servers facilities. Experimental observations indicated that the network data transmission delay has no serious effect on the resulting control performance in the FB implementation approach. However, the increase in the network transmission delay degrades the control performances in the NCS implementation approach. To improve the control performance due to the variable transmission delay degradation effect, a fuzzy PID control approach was proposed. In [88], experimental platform for NCS was designed and implemented. The system used control, video and ftp/web-data over CAN and switched Ethernet networks.

Recently, wireless networked control systems (WNCS) became an interesting area in research community, and in particular, designing WNCS over mobile ad-hoc network (MANET) brought new challenges to the researchers. In ad-hoc systems, strict guarantee for topology, delay etc. were not practical. A smart integration of communication network, computing and control was therefore required for quality performance of WNCS. In [89], the network, control and computing co-design issues were reviewed and guidelines for successful implementation were established. Some co-simulation tools for such systems were addressed. Important ideas for subsequent development were identified, including online co-simulation using MATLAB for control/computing, NS2/OPNET for communication networks and development of co-design theory and co-simulation tools for control, computing and communication.

The sampling period scheduling of NCSs with multiple control loops was addressed in [90]. The generalized exponential function was employed to describe integral absolute error (IAE) performance versus sampling period based on *True-*

Time toolbox where the sampling periods were scheduled to obtain the optimal integrated performance. Algorithms were developed to guarantee the stability of every control loop and the bandwidth on available network resource. In [91], the structure of NCS for immune PID controller was designed. The immune PID controller constituted by the combination of biological immune principles and traditional PID control had simple structure and algorithm, and with the features of strong robustness and adaptability, which can improve the control performance of the system further. Several results pertaining to the analysis and design of NCS were provided in [92] based on sampled-data, model-based, and hybrid models. Also, some of the most critical problems in the design of NCS such as packet loss, network induced time-delays, and limited communication in the control loop were presented.

With the emerging IP-based technologies, the quality of network traffic of a control system is becoming much more challenging. Operators must constantly monitor the state of traffic flow in the control system and decide whether the system is functioning properly. Obviously, the characteristics of normal traffic and extract boundary conditions, for example, thresholds, at which the quality of services begins to deteriorate to intolerable levels must be known. This will help distinguish safe traffic from an undesirable one. In [93], a network simulation technique was used to analyze the traffic behavior of IP-based control systems and construct a flexible simulation architecture. With focus on the message jitter, as it is embedded within the control loop, the implementation of NCS was considered in [94] where a strong impact on the control execution delay was recognized. By comparing the timing properties of both CAN and PROFIBUS control networks, the capability of the CAN network was assessed to fulfil control application requirements.

A new wireless communication architecture is specified in [95] that provides the required reliability, safety, security and real-time parameters for wireless sensor networks. The primary goals of the work were:

1. The implementation of a WirelessHART network simulator which is a new wireless protocol that aims to establish a new communication standard for process automation applications. Essentially, The simulator was written in **C++** and interfaced with MATLAB through a **S**-function, to have a friendly use of it. The possibility to work with this simulator was added in the *TrueTime* library giving to the user a very powerful tool to simulate different wireless scenarios.

2. The study of delay compensation in a WirelessHART network. This protocol provides for the synchronization between all the devices of the network. If the controller is not part of the wireless network, no synchronization with the other devices is guaranteed. In this condition, if the controller clock is affected by drift, a varying delay is introduced in the control-loop. This effect degrades the performance desired and, in some critical cases, causes instability to the whole system.

A framework for NCS simulation to enable the analysis of the influence of network transmissions on the performance of control systems was presented in [96]. An agent-based design was introduced to simulate data packet transmissions over the network. The network simulator 2-26 (NS-2.26) release was extended by modifying the user data protocol (UDP) common header in order to support transmission of application data. Then, modifying the network topology parameters, networked control system simulations are analyzed for different parameter changes, such as the network bandwidth, the number of plant nodes, and the sampling period. The off-line identification problem for open-loop stable LTI processes working in the networked environment was extensively studied in [97] with emphasis on the effects of random network-induced delays and packet dropouts based on event-driven actuators (D/A conversion) and a general non-uniformly non-synchronized sampled data. A modified version of the simplified refined instrumental variable method was developed to solve this problem, and was validated in a networked identification experiment using the simulator *True-Time*. The TCP/IP communication issue of data stream in NCS was investigated in [98]. Analytic model of TCP/IP was presented according to slow start theory. The simulation model was established based on OPNET software. By applying TCP or UDP to different data streams, the simulation results showed that real time and reliability of most data streams can be guaranteed.

Although the simulations and experimental investigation presented in this chapter are somehow inspired or in the line of the related work, but can't be directly compared with the other related works explicitly. For example, the simulation study of packet loss is uniquely investigated in the simulation set up. The laboratory plant and the LabVIEW program is uniquely used in the experimental study while the other related work use different set of plant and software.

3.3 Preliminary Simulations

It turns out from the foregoing discussions that designing a real-time control system is essentially a co-design problem since the choices made will affect the control design and vice-versa. Deciding on a particular network protocol will induce certain delay distributions that must be taken into account in the controller design. Alternatively, bandwidth requirements in the control loops will influence the choice of CPU and network speed. Therefore, using analysis tool like *Jitterbug*, one can compute a quadratic performance criterion for a linear control system under various timing conditions and model representations [99]. A stochastic timing model with random delays can be invoked to describe the execution of the system. Guided by this information, the user can proceed using a simulation tool such as *TrueTime* to perform event-based co-simulation of a multitasking real-time kernel containing controller tasks and the continuous dynamics of controlled plants. The simulations capture the true, timely behavior of real-time controller tasks and communication networks, and dynamic control and scheduling strategies can be evaluated from a control performance perspective. The controllers can be implemented as MATLAB **M**-functions, **C++** functions, or ordinary discrete-time Simulink blocks. The following subsections shed light of the simulation tools.

3.3.1 TrueTime

TrueTime [100] is a Matlab/Simulink based simulator which offers co-simulation of controller, network transmission, and plant dynamics. Introduced in 2002, TRUETIME is still evolving and currently a beta version 2 is available, although version 1.5 is considered as stable software. Main feature of TRUETIME is the use of real-time kernels in which controller tasks are executed. This environment can be used to study standard and distributed control, scheduling, overrun handling, synchronization, control over wireless networks, and wireless ad-hoc routing using AODV. The TRUETIME blocks can be connected with other Simulink blocks to

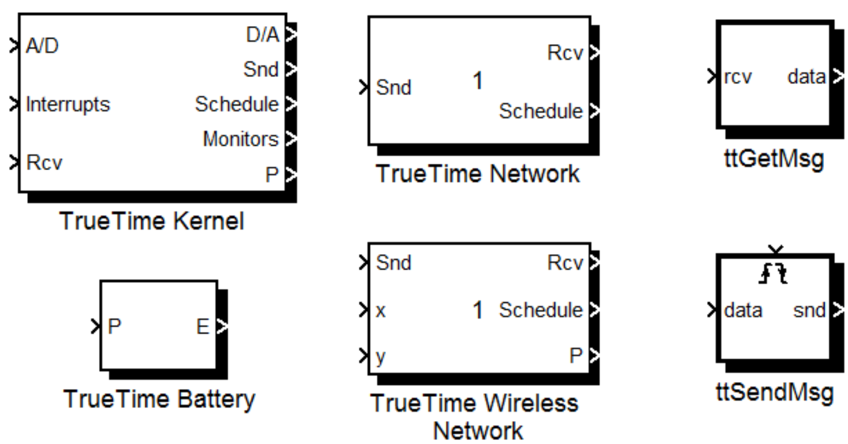

Figure 3.1: The TRUETIME 1.5 library blocks

form a real time distributed (networked) control system. The TRUETIME blocks additionally require to initialize the kernel and network blocks. This also requires to create tasks, interrupt handlers, timers, events, monitors, etc for the simulation environment to work.

TRUETIME network block simulates Medium Access and Packet Transmission in a Local Area Network (LAN) environment. A node uses *ttSendMsg* primitive function to transmit a message over network. This causes a triggering signal to the network block on the corresponding channel of node on the network. Version 1.5 of TRUETIME supports simple models of networks including: CSMA/CD (e.g., Ethernet), CSMA/AMP (e.g., CAN), Round Robin (e.g., Token Bus), FDMA, TDMA (e.g., TTP), and Switched Ethernet. The models ignore propagation delay since it is very small in LAN. Models support packet level simulation. Network parameters can be configured according to experiment include number of nodes connected to network, data rate in bits/s (i.e., speed of network), minimum frame size (bits), and loss probability from 0-1 (i.e., probability that message loss during transmission).

3.4 Simulation Examples

In what follows, we provide two representative examples

3.4.1 Example 1: Investigation of Control performance against loss probability (packet loss)

Control Performance versus Loss Probability is studied in this example. **Loss Probability** is the probability that a network message is lost during transmission. Lost messages will consume network bandwidth, but will never arrive at the destination. Example 1 is shown in Figure 3.2.

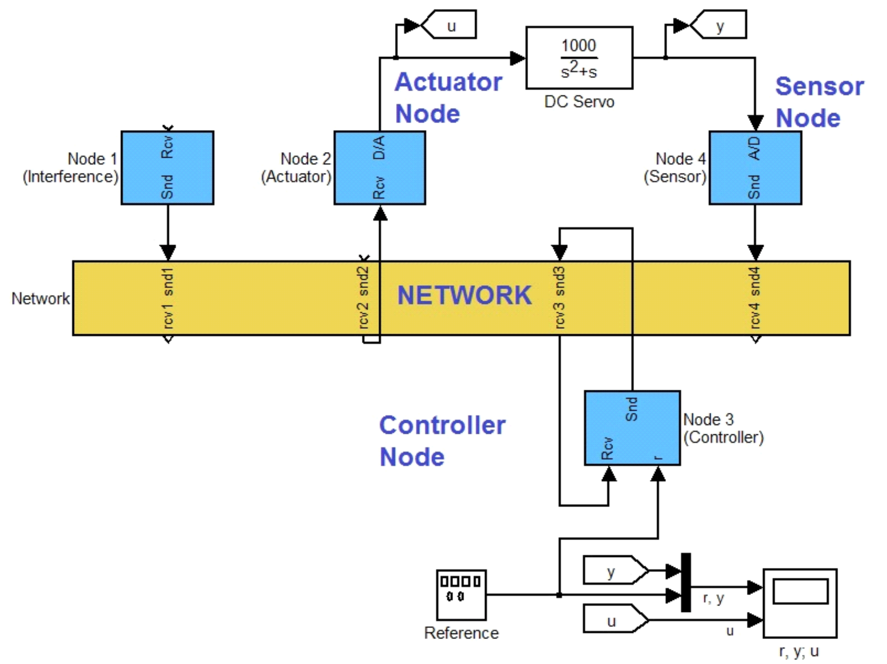

Figure 3.2: Simulation Example 1

Network Settings are:

Network Type: CSMA/CD (Ethernet)

Data rate : 80000 bits /sec

Minimum frame size: 40 bits

Loss probability: (0-1)

Investigation of control is observed for different values of Loss Probability. Figure 3.3 shows the reference, output and corresponding control signal when the loss probability of the network system is zero. Figure 3.4 shows the acceptable tracking with a control signal having values from -3 as minimum to +3 at maximum. Figure 3.5 shows the case when loss probability is 0.1. In this case we observe oscillations in tracking signal and an increasing effort in the control signal (i.e., maximum control signal goes to 6). Figure 3.6 shows the case when loss probability is 0.2 (i.e., 20%). In this case the tracking signal is exponentially increasing and oscillatory with high magnitude of control signal not feasible. This investigation illustrates that there is an upper bound on the packet loss (e.g., 0.2 here), beyond which networked system will become unstable.

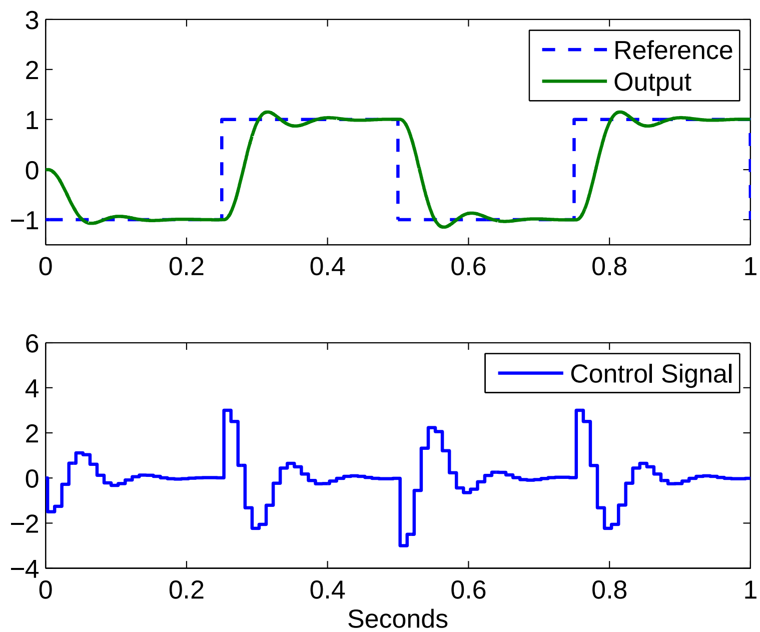

Figure 3.3: Loss Probability = 0

3.4.2 Example 2: Investigation of Tracking Error in different types of networks

Investigation of the system shown in Figure 3.2 is carried out for different networks providing same Loss Probability of 0.1. Figure 3.7 shows the tracking signal with respect to reference in case of different networks under similar conditions. The error (y-r) is shown in Figure 3.8.

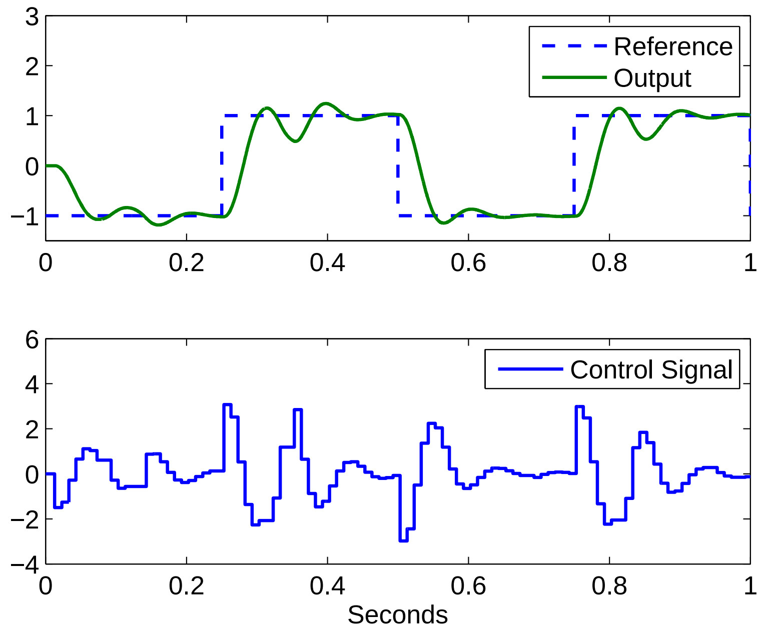

Figure 3.4: Loss Probability = 0.05

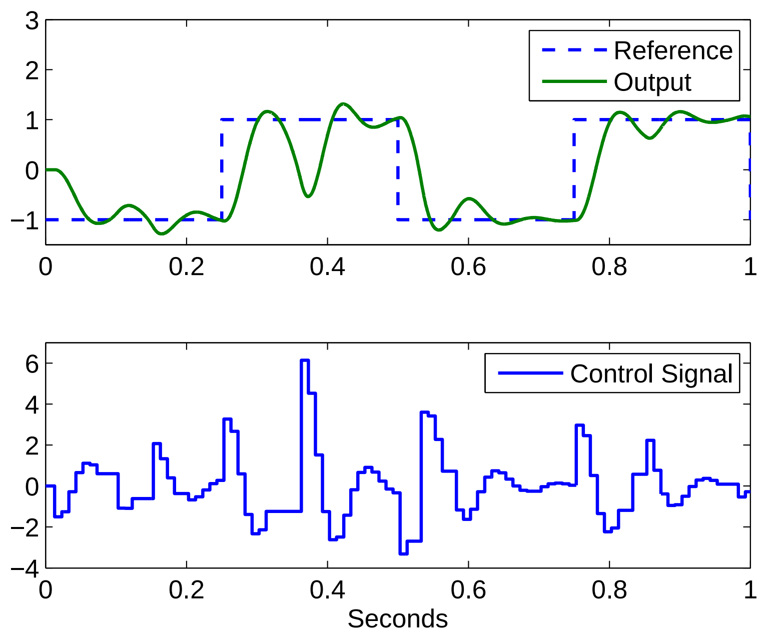

Figure 3.5: Loss Probability = 0.1

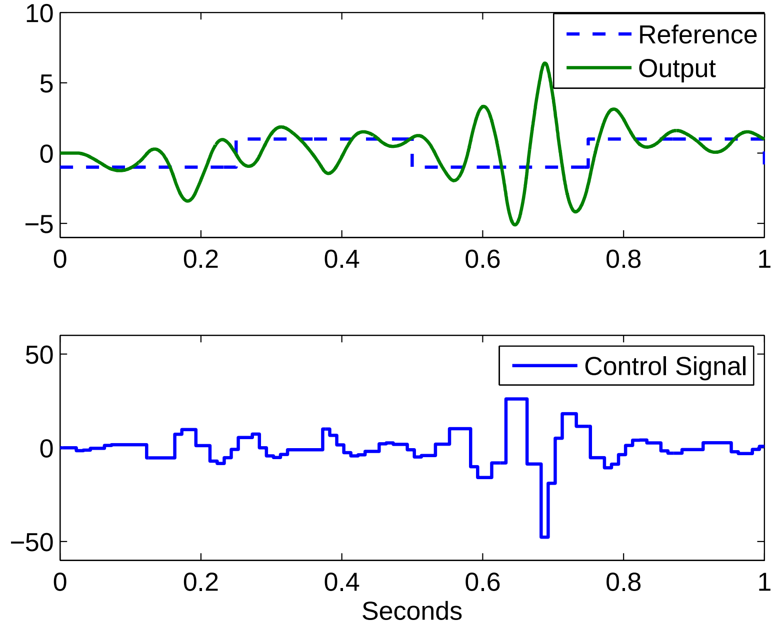

Figure 3.6: Loss Probability = 0.2

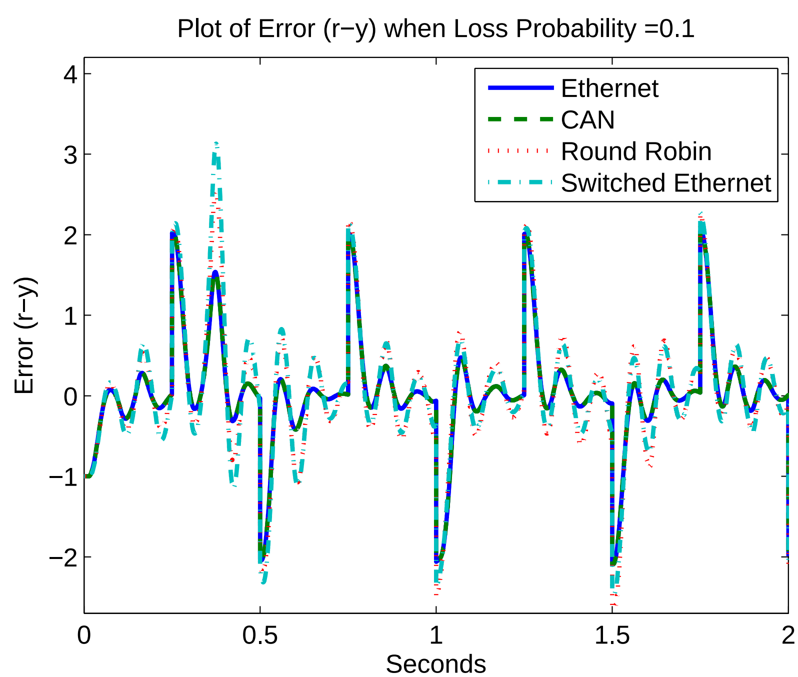

Figure 3.7: Output vs. Reference for different networks under similar condition and Loss probability of 0.1

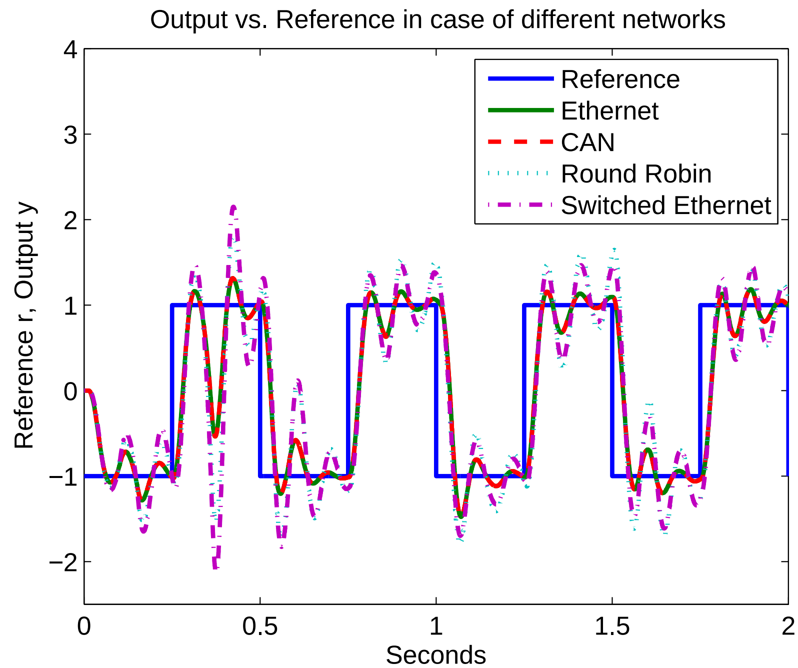

Figure 3.8: Error (r-y) in case of different networked under similar condition and Loss probability of 0.1.

The presence of packet loss in network causes overshoot and oscillatory response as shown in Figure 3.7 and Figure 3.8. Switched Ethernet shows larger error and oscillatory response, while Round Robin shows relatively less error. CAN network show the least error and least oscillations. This result is due to the fact that CAN network is deterministic, while Switched Ethernet is non-deterministic network. Moderate performance of Round Robin is due to the fact that it is based on token passing method and between node turns, the network is idle. In the simulated example, CAN network perform best, while the performance of Switched Ethernet is worst.

3.5 Experimental Set-Up

A coupled two-tank physical system is used to establish a network control system. In this experiment, the level of the tank is controlled using pump and the feedback signal from level sensor. This system consists of two tanks which are coupled through a manual valve. Another manual valve is also provided at bottom of each tank for drain and can be used to illustrate tank leak or disturbance in the level. Each tank can be filled with a pump operating with a control signal of 0-10 volts. Each tank can be probed with a level sensor (0-10 volts analog input signal) and a flow meter (0-10 volts analog input signal).

The pump and level sensor on the physical system are connected to a Plant-PC via USB based Data Acquisition card. This Plant-PC is connected on Local Area Network. The Sensor information is transmitted to remote PC (which is Monitoring and Controller PC) on the network via TCP/IP communication protocol. Data Acquisition, TCP/IP communication and Graphical User Interface are build in LABVIEW software from National Instruments. Graphical block diagram of this experimental set-up is shown in Figure 3.9.

3.5.1 Brief description of the network

The Local Area Network consists of about 700 nodes. A node means a network device having IP (Internet Protocol) address. These nodes include Servers, Laboratory Computers, Office Computers, Networked Printers etc. Network is deployed with Category 5 (i.e., CAT5) and CAT6 cabling standards. The external

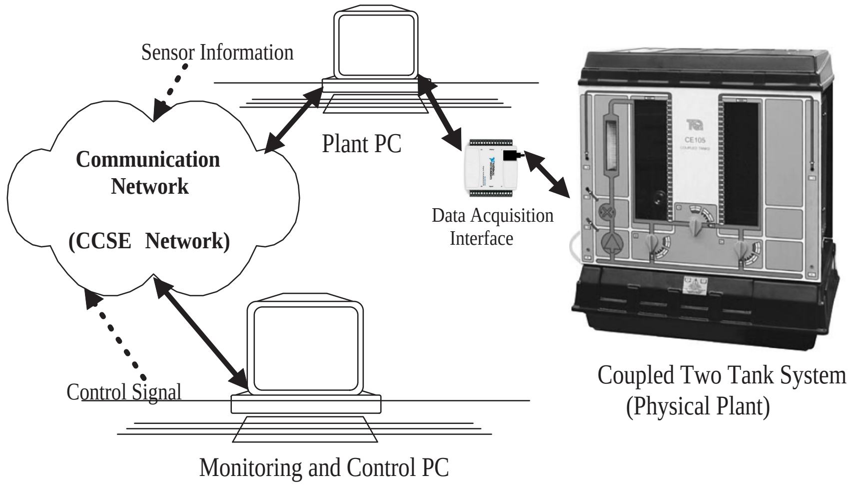

Figure 3.9: Networked two-tank system

gateway is connected through CAT5. One switch at OSI Layer 3 is used for the external gateway, while 60 switches at OSI Layer 2 are used for the distribution of nodes in the LAN. Services provided include file sharing, internet access, on-line printing etc to name few.

3.5.2 Description of plant and controller

The Ethernet based Networked Control System of the Two-Tank process is illustrated in Fig.3.9. The plant PC is connected to the Two-Tank process. Analog Input Channel is connected to the Level Sensor (0-10 volts), and Analog Output is connected to the Pump. National Instruments USB-DAQ is used for the Interfacing. TCP/IP connection is established between the Two PCs (i.e., Plant PC and Controller PC) over CCSE Network, which is the Local Area Network of the University Campus. A Manual knob through User Interface on Controller PC is used to send Control Signal to Plant PC and is applied to the Two Tank system via USB-DAQ. Control Signal from remote Controller PC is also displayed on the Plant PC's Front Panel. Reference Signal is set from Front Panel of Plant PC and can be send from the Controller PC. Successfully established TCP/IP connection between Plant PC and Controller PC. Control Action received from Networked Controller PC is implemented to the Two-Tank System (Practical System) connected to Plant PC.

3.6 Description of programming software:

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is used as the development environment for the experimental setup in this chapter. LabVIEW is a Graphical Language from National Instruments that gives integration with data acquisition for measurement and control applications enabling wide range of connectivity options. A simple LABVIEW program is called Virtual Instrument (VI), which consists of two parts: (1) Front Panel, and (2) Block Diagram. Front Panel of a Virtual Instrument works like an HMI (Human Machine Interface) for user input and display, while block diagram is the data-flow code behind the front panel where programming is done through built in function blocks. The front panel for Plant PC is shown in Figure 3.10 while front panel for Controller PC is not shown due to simplicity. Block diagrams for Plant PC and Controller PC are shown in Figures 3.11 and 3.12 respectively to help the reader from programming view point.

After successful setup of the networked control system as depicted in Fig.3.9,

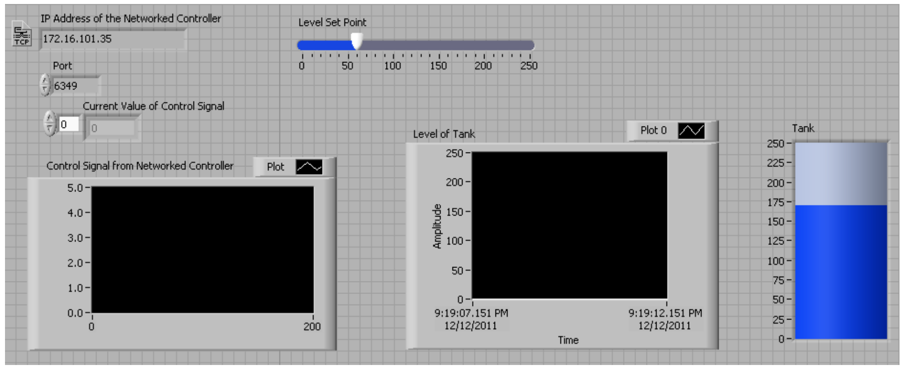

Figure 3.10: Front Panel of Plant PC

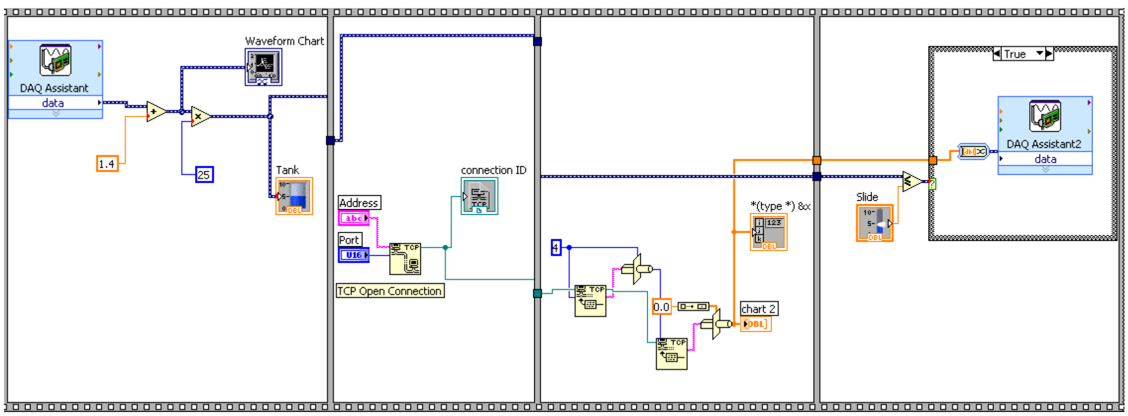

Figure 3.11: Block Diagram of Plant PC

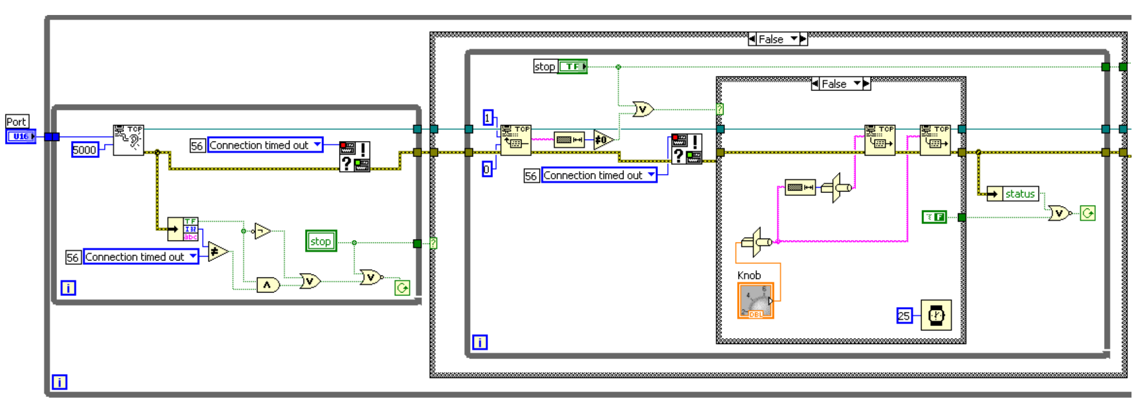

Figure 3.12: Block Diagram of Networked Controller PC

we conducted several investigations by changing the proportional gain of the networked controller. Proportional gain of the level controller is varied from 0.2, 0.3, 0.4, 0.5, 1 and 1.5. Level measurements are taken on local and remote computer to study the possible delay in measurements. Fig.3.13 shows the Local and Networked Level Measurement (a), Set Point and current PV (level) (b), Control Signal from Networked Controller (c), and Error (SP-PV) (d). Fig.3.14 is a zoomed view of local and networked measurement and a delay can be seen. Fig.3.15 shows the error in case of different values of proportional gain. The error with $K_p = 1.5$ provides minimum steady state error.

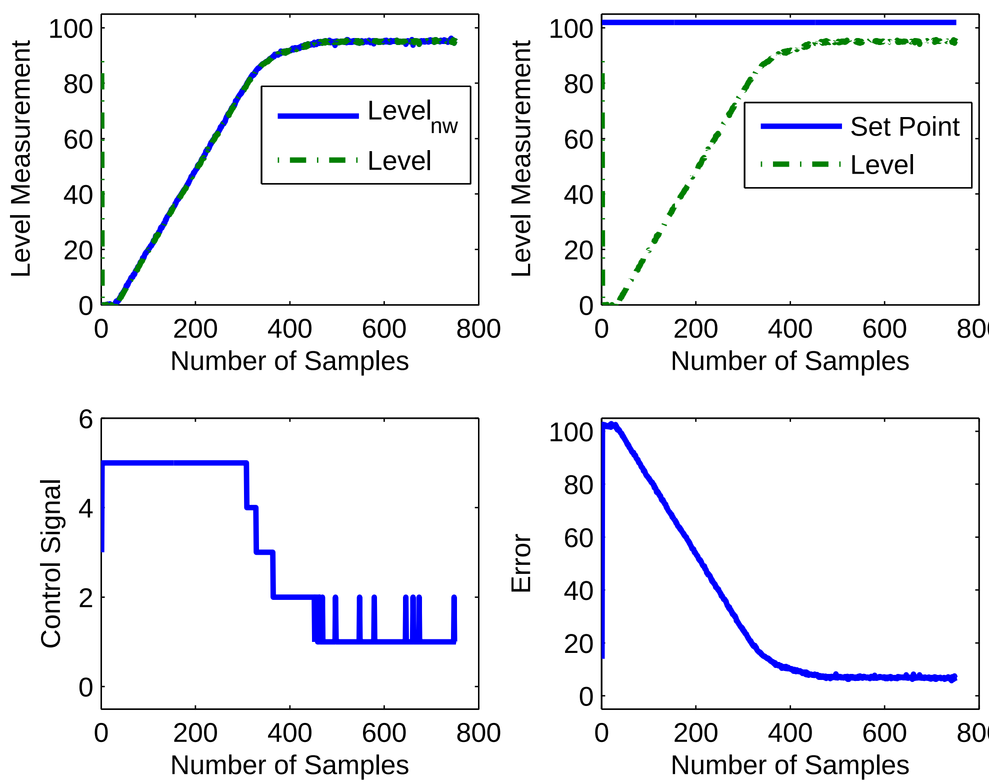

Figure 3.13: For Kp=0.2, (a) Local and Networked Level Measurement (b) Set Point and current PV (level) (c) Control Signal from Networked Controller (d) Error (SP-PV)

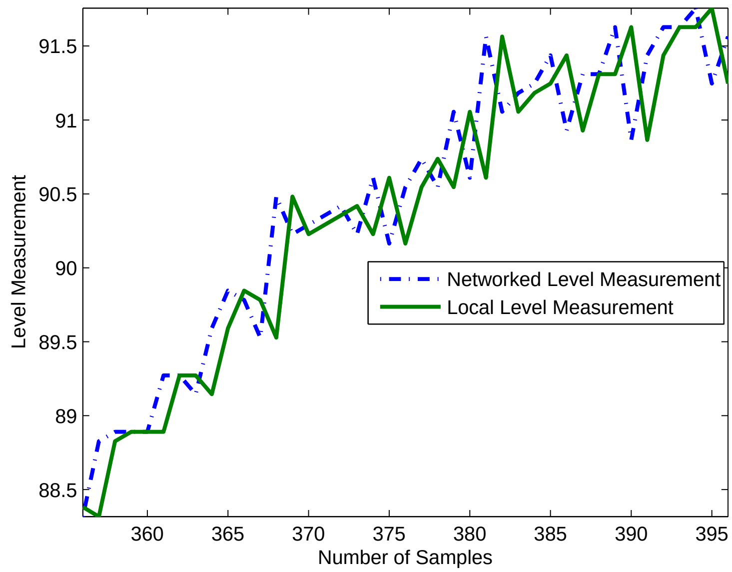

Figure 3.14: Local and Networked Measurement: Zoomed View

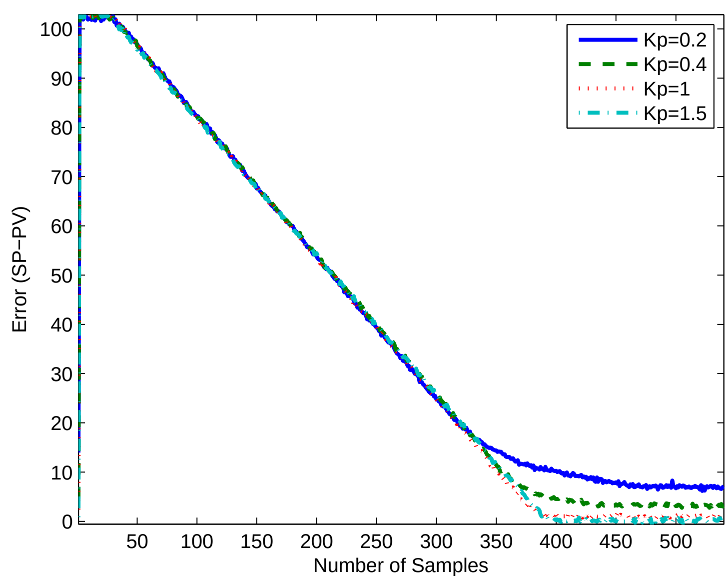

Figure 3.15: Error Comparison for different Kp

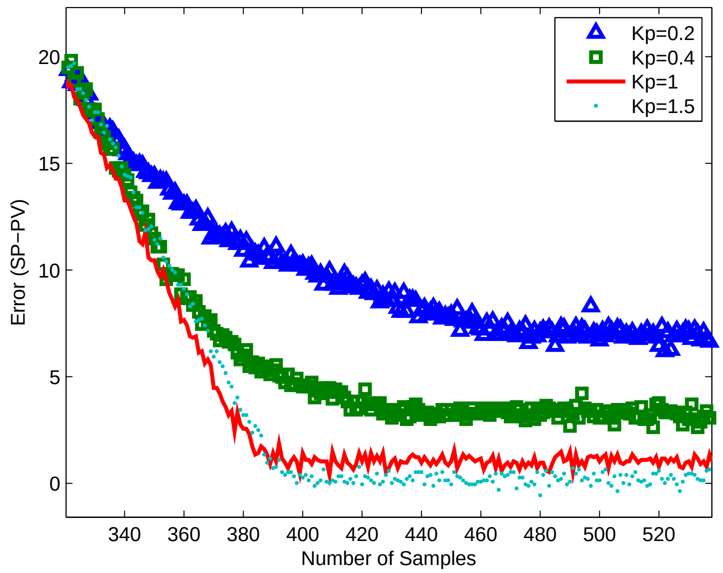

Figure 3.16: Error Comparison for different Kp: Zoomed View

3.7 Conclusions

In view of the increasing research activities of distributed control systems, this chapter has

- reviewed simulation tools and experimental setups for distributed and networked control systems
- established experimental setup for networked control systems
- performed simulations to investigate the stability of a dc servo motor in networked scenario against different loss probabilities.
- studied effect of different networks on the control performance is investigated with a simulation study for fixed packet loss case.

Both the simulation and experimental investigations indicate promising results and have brought encouraging experience to the authors to expand the research in a co-experimental-simulation environment to expand the research and to contribute improved results to the community of control systems.

The work presented in this chapter contributes further to the efforts made by other researchers in the experimental and simulation sides of the field of distributed and networked control systems. Essentially, it tries to motivate the existing efforts and shows interesting areas of research by using co-simulations and experimental efforts in addition to using existing Ethernet to provide communication link between different units of a distributed system. Briefly stated, this work has uniquely investigated:

- the effect of packet loss on stability of a networked control system,
- the effect of different type of network on the control performance,
- observation of the delay of measurement experimentally and
- the different steady state errors when changing the proportional gain of controller

CHAPTER 4

OUTPUT FEEDBACK EVENT-TRIGGERED CONTROL FOR DNCS

This chapter addresses the problem of output-feedback communication and control with event-triggered framework in the context of distributed networked control systems. The design problem of the event-triggered output-feedback control is proposed as a linear matrix inequality (LMI) feasibility problem. The scheme is developed for the distributed system where only partial states are available. In this scheme, a subsystem uses local observers and share its information to its neighbors only when the subsystem's local error exceeds a specified threshold. The developed method is illustrate by using a coupled cart example from literature.

4.1 Introduction

4.1.1 Motivation

The advancement of computational and communication technology, and accessibility with open standard interfaces have relaxed the hard-requirement of simple algorithms at sensing and actuation devices. In turn, this has encouraged to design intelligent and smart sensing and actuation devices for control applications. These distributed smart devices can be configured from controllers with appropriate sensing and control schemes to meet the distributed control objectives. In addition, the wireless technology has enabled to realize a type of distributed control systems embedded with wireless nodes, thus asking for resource efficient control and communication algorithms. Such systems require to limit the use of sensing, communicating and control to the time instances when the system needs attention. Recall that the classical sampled-data control is based on periodic sensing, control calculation, and actuation irrespective weather there is change in sensing or new control calculation is needed [20]. Many simulation and experimental studies show that event-triggered control strategy is capable of reducing the number of control calculations with satisfactory closed-loop performance, see, e.g., [60], [14], [15], the stable control algorithms in distributed networked control paradigm is rare. In this regard, we have studied the problem of event based output-feedback control in the context of distributed networked systems.

Event-triggered control (ETC) is a control strategy that is especially suited for applications where communication resources are scarce [101]. By updating and communicating sensor and actuator data only when needed for stability or performance purposes, ETC is capable of reducing the amount of communications, while still retaining a satisfactory closed-loop performance. In an event-triggered scheme, a control task is triggered by the violation of the so-called "event condition", which is usually based on the actual state of the plant. Because the event-triggered control enables the task periods to vary with the system state, it can generate longer task periods than the time-triggered control. Hence, it can improve the effective usage of system resources. Furthermore, it leads to a better overall system performance, i.e., a trade-off between the control performance (tracking, stabilization, and disturbance rejection), software performance (processor load), and other aspects (communication bus load and system cost, see [73]).

Furthermore, since sensor and actuator nodes can be physically distributed, centralized event-triggering mechanisms are often prohibitive and, therefore, we will propose a decentralized event-triggering mechanism. This event-triggering mechanism invokes transmission of the outputs in a node when the difference between the current values of the outputs in the node and their previously transmitted values becomes large compared to the current values and an additional threshold.

4.1.2 Limitations in existing literature

A majority of the literature on event-triggered control is based on the state-feedback control methods [102]. In many control applications complete state measurement may not be available for feedback. In case full state is not available, the output-feedback controllers are required. The problem of event-triggered output-feedback control is still open problem. To truly realize the benefits of event-triggering, one would need an event-triggered output feedback controller, in which triggering is done solely on the basis of observed sensor measurements, rather than state estimates [2]. This chapter studies the problem of event-triggered output feedback control in the scenario of distributed networked control systems. Extension of existing state-feedback event-triggered control communication and control methods to output-feedback scheme is not straightforward and may result in Zeno behavior [102]. Another requirement of the event based scheme is to keep a minimum-time between two subsequent events [102] in addition of the stability of the overall scheme. Notice that the Zeno behavior in which the inter-event time converges to zero, also makes practical implementation of any event-based scheme difficult. The sensors, actuators and controller nodes in a networked system can be physically distributed, thus a distributed triggering is required instead of centralized scheme. This encourages to investigate the event-based methods for communication and control in the distributed networked framework.

Networked based systems raise several issues including energy, continuous data, synchronization and congestion. Such networked-related problems have been addressed by several researchers. In [103], the issue of energy and continuous data is addressed by discussing an energy-efficient framework for data collection based on clustering in wireless sensor networks. Integrated prediction and clustering techniques, enables a reducing communication cost and applies sleep/awake scheduling for efficient energy framework. An application layer data throughput prediction and optimization service is designed and implemented in [104] for many-tasks computing in distributed environment. The scheme uses multiple parallel TCP streams to improve end-to-end throughput of data transfer and to avoid congestion. Challenges design, and performance aspect for large scale distributed computing environment is addressed in [105]. Body sensor networks (BSN) are used to monitor health by using biosensors distributed over the human body at different positions. Time synchronization and low-energy communication are two challenges in the biosensor network. In [106], an energy efficient scheme was proposed the body sensor networks based on a hybrid multihop network structure. In [107], dynamic scheduling for wireless data networks is proposed to solve network congestion problem, where wireless transmission is modeled by considering interference and the adaptive transmission rate. A codesign approach is presented in [108] for the structure health monitoring of distributed civil structures, an important cyber-physical system application. The scheme uses wireless sensor network for the detection of damage and its location. The key requirement of such applications is the energy efficiency and event based sensing in the wireless sensor networks.

4.1.3 Why think of Output Feedback?

One objective in the control theory is to achieve good control performance with resource efficient control scheme. State-feedback control scheme requires full states of the plant. State Feedback allows a rich and sophisticated approach to design a controller. For example:

- One can position the poles anywhere at the desired location (but at cost of high control gains), in the left half plane,
- One can use design tools like LQR regulator directly

The first advantage of full state feedback is that it gives complete control over placement of the closed loop eigenvalues. Second, if a Kalman filter or observer is required to construct the states for feedback, the separation theorem guarantees that the system closed loop eigenvalues consist of the filter eigenvalues together with the controller eigenvalues, each computed as if they were operating separately. Finally, the method can be extended to multi-variable control by use of LQG optimal control theory. In fact state feedback allows us to position the closed loop poles anywhere we want by using any pole placement methods (Ackermann, etc); the problem is that we should have a very reliable process model because the state estimation calculated by the state observer will be based on that and the state feedback gains too, so if there is a mismatch between the real process and our model the poles can go unstable in worst case. The control algorithms based on the actual process response (output) are far more robust and reliable than those based on process models, unless we have a way to keep the model precisely updated. We should recall the that, there are some cases when we should use state feedback instead of output feedback. For example, when there are unstable modes that are uncontrollable from the output, but can be controlled by other states. Such cases are exceptional for output feedback control methods.

4.2 Related Work

Little work has been done for event-triggered output feedback control. It is worth to mention that most of the prior work about the event-triggered and self-triggered control concentrates on the state-feedback controllers. So far, only few studies have been carried for the output-feedback controllers. An event-triggered implementation based on a dynamic output-feedback controller was shown in [109]. Recently, a dynamic output-feedback control system under a modified event-triggering mechanism was modeled as an impulsive system in [110]. Conditions on its stability and L_∞ gain performance were derived in terms of LMIs. A guaranteed minimum inter-event time was also presented. In [111], an observer structure from [112] is combined with the self-triggered state-feedback controller proposed in [113] to form an output feedback configuration. Here, the event triggering is designed on basis of the Lyapunov function between the sampling events. In [114], previous work of [111] is extended to the case of acyclically interconnected systems. [110] proposed an event-triggering mechanism that invokes execution of the control task when the difference between the measured output or the control input of the plant or controller, respectively, and its previously sampled value becomes large compared to its current value and an additional threshold. [115] examined output feedback control of wireless networked control systems where there are separate links between the sensor-to-controller and controller-to-actuator. The proposed triggering events only rely on local information so that the transmissions from the sensor and controller subsystems are not necessarily synchronized. An upper bound on the optimal cost attained by the closed-loop system is established for the weakly coupled case. [116] investigated both reduced and full order observers for linear system with event-triggered sensing scheme. Global uniform ultimate bounded stability of the closed-loop systems is established with the event-triggered scheme.

In [117], an observer based output-feedback control scheme is presented in event-triggered framework. This scheme uses a state observer in the event generator and shows the communication frequency is bounded. This work can be extended by including a disturbance estimator to the observer that will enable the event generator and the control input generator to have an estimate of the disturbance. The additional information about system disturbances can be used to further increase the inter-sampling time of event triggering. Other event-Triggered methods based on output information instead of full state information are discussed in [110], [118], [119], and [120]. The Luenberger state observer of the event generator in [117] is assumed to continuously receive the measured output. In [110], the measured output is directly used to update the control signal at event times and there is no observer as compared to [117]. While in [118], [119] and [120], Event based Kalman filter is used to estimate the state from the event-sampled measured output. [118] extended the work of [121] by determining suboptimal event-triggers in finite-horizon output-feedback problems.

In [122], triggering events are proposed for weakly coupled output feedback control of wireless networked control systems. The weakly coupling in [122] relaxes the strongly coupling requirement of [110]. In [123], distributed estimation over wireless sensor networks (WNSs) is presented based on event-based technique. The methodology is based on a combination of local observers and a consensus strategy. The observers are designed using LMI assuming periodic communication, which are deployed with an event-based strategy to reduce the network traffic. [124] discussed three output feedback architectures depending weather the controller and sensor are co-located or not. The observer and controller gains are calculated independently and the inter-sample times are conservative. Most of the proposed event-triggering conditions depend only on local information and include explicit positive lower thresholds for inter-sampling times that are designed to ensure global asymptotic stability of the closed loop system. In comparison, [110] proposed an event-triggered implementation that guarantees uniform ultimate boundedness of the plant state and a semi-global estimate of the minimum intercommunication time (dependent on the initial state of the dynamic controller and the unknown state of the plant).

In [117], a model based output feedback controller was proposed, in which the communication from the observer subsystem to the system model subsystem is triggered whenever a condition comparing the observer state and the state of a local copy of the system model exceeds a threshold. This controller guarantees a positive minimum transmission time and uniform ultimate boundedness of the closed loop state. In [118], [122] event-triggered output feedback control for discrete-time systems was studied as an optimal control problem, explicitly involving communication costs. The proposed architecture includes a Kalman filter in the sensor subsystem and identical observers in the sensor as well as actuator subsystems. The results provide an upper bound on the optimal cost attained by the event-triggered system. In comparison to [117], [118], [122], we do not require identical observers/models to be run at different locations. Recently, a self-triggered dynamic output feedback controller was proposed in [114] where a discrete-time observer is in cascade with a full state-feedback self-triggered controller. The resulting closed loop system is rendered input-to-state stable (ISS) with respect to exogenous disturbances.

In [125], the authors focused on the design of the event-triggered control when the full state can not be available. Event condition is based on the output error and asymptotic stability is given in terms of an LMI (Linear Matrix Inequality). In [126], an event-triggered control for networked control systems is discussed in passivity based I/O framework, where triggering condition is based on the passivity theorem. [126] studied the network induced delays and studies the finite-gain L_2 stability from external disturbance to the plant output.

4.3 Problem Formulation

Consider a distributed networked control system consisting of N agents (or subsystems). An agent can be a subsystem, or an individual plant. See Figure 4.1 for graphic illustration of such system with three agents. Each agent consists of a physical component (responsible for system dynamics) and a cyber component (responsible for control & communication). The physical components are interconnected as shown by the solid lines in the figure, while the cyber components are interconnected through communication network as shown by dashed lines in the figure. A model of distributed networked control system is discussed in [2] assuming state-feedback control. The model is further used in [11] for event-triggered data transmission in distributed networked control systems with packet loss and transmission delay. In this chapter, we extend the the state feedback scenario of [11] to the output feedback case. In case of output feedback, the states are partially known, and local observers are designed to estimate the states. The observer estimated states can be shared to the appropriate neighboring subsystem according to the overall control objectives of the distributed system. It is assumed that the subsystems have interacting dynamics, and thus require dynamic information from the neighboring subsystem. The control law is designed into two parts. One part is dependent on the local observed states, and the second part is based on the information received via network for the interacting dynamics of other subsystems.

Remark 4.3.1 In case of large number of subsystem states, sharing the outputs will further reduce the network traffic in the distributed system.

The distributed networked control system with output feedback is shown in Fig. 4.1. The defining features of a distributed networked control system are: (1)

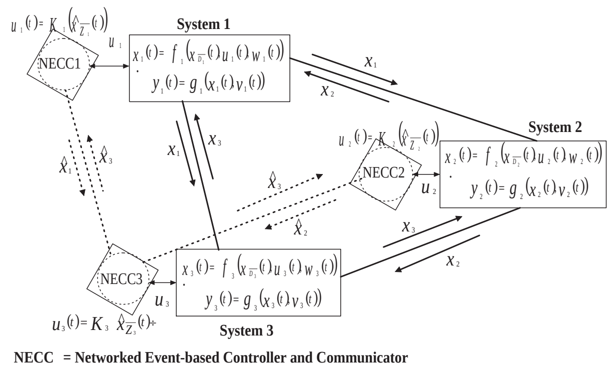

Figure 4.1: Event-Triggered Distributed Networked Control System with Output Feedback

The plant is consisting of subsystems with individual controllers, (2) the output of one subsystem is the input for the other subsystem resulting in a cascaded interconnected system, (3) the sensors, actuators and controllers are connected via a communication data network as illustrated in Fig. 4.1.

The distributed networked control system consisting of N subsystems can illustrated in Fig. 4.1 when $N = 3$. Each subsystem consists of a physical component (responsible for system dynamics) and a cyber component (responsible for control & communication). We can introduce a unifying cyber component for generality that may represent sensor, actuator and/or controller as networked event-based controller and communicator (NECC), as shown in Fig. 4.1. The physical connection between the subsystems is represented by the solid lines, and the communication link between the cyber components ($NECC_i$) is shown by dashed lines, respectively in the Fig. 4.1. The distributed networked framework discussed in this section is taken from [2].

4.3.1 Graph theoretical representation of DNCS

The distributed networked system as shown in Fig. 4.1, can be described and analyzed in the notion of the graph theory. In graph theory, several objects (subsystems) along with their interconnected relationship are modeled as graphs. These graphs can be viewed as mathematical structures illustrating the relational behavior of the subsystems. The subsystems (i.e., objects) are known as *vertices*, and the interconnecting lines are called *edges*. This section presents the graph theoretical representation of the DNCS system based on [2]. The Fig. 4.1 represents three vertices (i.e., subsystems), three physical-edges (solid lines), and two cyber-edges (communication links between system 1-3, and system 2-3).

For general discussion, the overall distributed networked control system can be divided into two graphs: (1) physical coupling graph ($\mathcal{G}_{phy}$), and (2) communication graph ($\mathcal{G}_{comm}$).

Physical coupling graph

Physical coupling graph consists of physical-edges and physical-vertices. Let $E_{phy} \subset \mathcal{N} \times \mathcal{N}$ represents the set of edges in the physical-graph $\mathcal{G}_{phy}$. Since, each physical subsystem is assumed to have a corresponding cyber-subsystem (i.e., NECC), therefore the number of vertices in physical and communication graph are same. Let, $\mathcal{N}$ represents the vertices of the physical-graph as well as for the communication graph, where $\mathcal{N} = 1, 2, ..., N$ is the set of the subsystems. Hence, a graph $\mathcal{G}_{phy} = (\mathcal{N}, E_{phy})$ represents the physical coupling between the individual subsystems, where $E_{phy} \subset \mathcal{N} \times \mathcal{N}$ is the set of edges in the physical graph. Note that, an edge (i, j) is considered in E_{phy} if the dynamics of subsystem j's physical component are directly driven by subsystem i's local state. To further elaborate, two corresponding neighborhoods (D_i, and S_i) in physical graphs are introduced to show the driving and driven-by character between the subsystems in physical interaction. The set $D_i = \{j \in \mathcal{N} | (j, i) \in E_{phy}\}$ contain the subsystems which physical drive the i subsystem. The set $S_i = \{j \in \mathcal{N} | (j, i) \in E_{cp}\}$ includes the subsystems which are drive-by the subsystem i.

Communication graph

Communication graph consists of communication-edges and communication-vertices. Let $E_{cm} \subset \mathcal{N} \times \mathcal{N}$ represents the edges of the graph $\mathcal{G}_{communication}$. The graph $\mathcal{G}_{cm} = (\mathcal{N}, E_{cm})$ represents the interconnections between the cyber-components of the subsystems. $\mathcal{N}$ denotes the vertices (i.e., nodes) of the graph and $E_{cm} \subset \mathcal{N} \times \mathcal{N}$ represents the edges of the graph. The set $Z_i = \{j \in \mathcal{N} | (j, i) \in E_{cm}\}$ represents the subsystems who can send information to subsystem i. The set $U_i = \{j \in \mathcal{N} | (j, i) \in E_{cm}\}$ contain the subsystem who can receive information from subsystem i. Assume $|\Sigma|$ = number of elements in the set $\overline{\Sigma} = \Sigma \cup i$, where $\Sigma \subset \mathcal{N}$ is any set discussed above.

Dynamical model of DNCS

Assuming x_i represent the local state of a subsystem in the distributed networked system, the dynamics can be represented by Eq. 4.1.

$$\dot{x}_i(t) = f_i(x_{\overline{D}_i}(t), u_i(t), w_i(t)), \quad x_i(t_0) = x_{i0} \tag{4.1}$$

where $x_i : \mathcal{R} \to \mathcal{R}^n$, $x_{\overline{D}_i} = \{x_j\}_{j \in \overline{D}_i}$ are the local states of subsystem i's neighbors that are physically connected to it. The system dynamics are characterized by the function $f_i : \mathcal{R}^{n|\overline{D}_i|} \times \mathcal{R}^m \times \mathcal{R}^l \to \mathcal{R}^n$ is continuous and locally Lipschitz satisfying $f_i(0,0,0) = 0$. $u_i : \mathcal{R} \to \mathcal{R}^m$ is a control input generated by the cyber-component of the subsystem and $w_i : \mathcal{R} \to \mathcal{R}^l$ is an external disturbance.

Assuming that the subsystem i can only detect its own state, X_i, and receive the broadcast states of its neighbors in Z_i. If some local error increases a threshold, subsystem i will sample and broadcast its state information to all subsystems in the set U_i over a real-time network. The control u_i, generated by subsystem i's cyber-component is computed based on the latest states that were successfully broadcast by those subsystems in $\overline{Z}_i$. These broadcast states are represented by $\hat{x}_{\overline{Z}_i}(t)$. Thus, the control signal, used by subsystem i is computed based on $\hat{x}_{\overline{Z}_i}(t)$, and can be written as

$$u_i(t) = g_i(\hat{x}_{\overline{Z}_i}(t)) \tag{4.2}$$

The corresponding linear form of the distributed networked control system can be represented as:

$$
\begin{aligned}
\dot{x}_i(t) &= A_{ii}x_i(t) + B_i u_i(t) + \sum_{j \in D_i} A_{ij}x_j(t) + C_i w_i(t) \\
u_i(t) &= K_{ii}\hat{x}_i(t) + \sum_{j \in Z_i} K_{ij}\hat{x}_j(t)
\end{aligned} \tag{4.3}
$$

4.4 Event-Triggered Output Feedback Control

The existing work on event-triggered output feedback is limited to either single control loops [117] or strongly coupled distributed systems [102]. This work studies the output feedback control of distributed networked control systems where sensors, actuators and controllers are connected over shared communication network. The distributed event-triggering depends on local information at the subsystem and thus relaxes the synchronization requirement of the subsystems. The chapter presents the LMI formulation of the Event-Triggered Output Feedback control by solving the feasibility of the proposed LMI system to get a stable closed-loop system.

4.4.1 The Method

This section shows how to implement the distributed output feedback scheme for linear distributed networked control systems. This notion of L_2 stability is used for stability analysis. For linear systems, events are designed by solving LMI feasibility problems. Consider the distributed networked control system with individual plant i dynamics given by

$$\begin{aligned} \dot{x}_i(t) &= A_{ii}x_i(t) + B_i u_i(t) + \sum_{j \in D_i} A_{ij} x_j(t) + \Gamma_i w_i(t) \\ y_i(t) &= C_{ii} x_i(t) + \sum_{j \in Z_i} C_{ij} \tilde{x}_j(t) \end{aligned} \tag{4.4}$$

Let the structure of the distributed observer is

$$\begin{aligned} \dot{\tilde{x}}_i(t) &= A_{ii}\tilde{x}_i(t) + B_i u_i(t) + L_i[y_i - \tilde{y}_i] \\ \tilde{y}_i(t) &= C_{ii}\tilde{x}_i(t) + \sum_{j \in Z_i} D_{ij} \tilde{x}_j(t) \end{aligned} \tag{4.5}$$

where,

- x_i, y_i, and u_i are physical variables representing physical coupling
- $\tilde{x}_i$ and $\hat{y}_i$ are observer variables
- $\hat{y}_i$ is networked variable.

Since, the event-triggered communication and control aims to reduce the network traffic over the control network, the delay and packet drop is reduced inherently. The event-triggering scheme is not dependent on time, and therefore, the delay and packet drop is not that important in an event-triggered scheme as compared to the time-triggered scheme. In event-triggered control, time is not critical and the sensing and control is based on an event. Therefore, the network properties are not critical in event-triggered control as they are in time-triggered control.

The interacting dynamics of the distributed networked control system, require that the control action at the local subsystem should be calculated based on the locally observed dynamics as well as on the information-dynamics of the interacting subsystem. Thus, the controller at the subsystem i is given by

$$u_i(t) = K_{ii}\tilde{x}_i(t) + \sum_{j \in Z_i} K_{ij}\hat{x}_j(t) \tag{4.6}$$

where, K_{ii} is the gain matrix corresponding to locally observed dynamics $\tilde{x}_i(t)$, and K_{ij} corresponds to the interacting dynamics $\hat{x}_j(t)$ of subsystems in the interacting set Z_i.

This is an observer based output feedback control system because the control decision is based on the output of the process without having the actual state of the system. The proposed system uses output of the process to calculate an estimation of state for communication and control purpose.

Assuming that the individual dynamics of each subsystem is same, we can combine overall DNCS system can be into following notation for unified analysis and design purpose. The overall plant is represented by

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + \Gamma w(t) && (4.7) \\ y(t) &= Cx(t), && (4.8) \end{aligned}$$

where $x = (x_1^T, \ldots, x_N^T)^T, u = (u_1^T, \ldots, u_N^T)^T, w = (w_1^T, \ldots, w_N^T)^T$, and $\hat{x} = (\hat{x}_1^T, \ldots, \hat{x}_N^T)^T$. Overall distributed observer system is given by

$$\dot{\tilde{x}}(t) = A_d\tilde{x}(t) + Bu(t) + L[y - \tilde{y}] \tag{4.9}$$

$$\tilde{y}(t) = C\tilde{x}(t), \tag{4.10}$$

where $x = (x_1^T, \ldots, x_N^T)^T, u = (u_1^T, \ldots, u_N^T)^T, w = (w_1^T, \ldots, w_N^T)^T$, and $\hat{x} = (\hat{x}_1^T, \ldots, \hat{x}_N^T)^T$. and, the distributed controllers take the following form

$$u(t) = K_l\tilde{x}(t) + K_n\hat{x}(t) \tag{4.11}$$

where $u = (u_1^T, \ldots, u_N^T)^T, \tilde{x} = (\tilde{x}_1^T, \ldots, \tilde{x}_N^T)^T$, $\hat{x} = (\hat{x}_1^T, \ldots, \hat{x}_N^T)^T, K_l = (Kl_1, \ldots, Kl_N), K_n = (Kn_1, \ldots, Kn_N)$. Assuming that $dim(K_l) = dim(K_n)$ for the symmetric case.

The control action in 4.11 is event-based due to the fact that $t \in [r_k^i, f_k^i)$, where $r_{kk}^i = 1^\infty$ is the transmission release time sequence, and $f_{kk}^i = 1^\infty$ is the transmission finishing time sequence for a transmission message from system i. Here, r_k^i, and f_k^i are monotonically increasing sequences corresponding to system i. The transmission and the control is based on the event-triggered values, which makes the control in 4.11 different from time-triggered control.

Remark 4.4.1 This work is an extension of [11] for the case of output-feedback control. Moreover, in [11], all the states of the subsystem are broadcasted which may not be required. Thus, in our work, we target to communicate the outputs of the system which reduces the communication burden and network traffic. This work assumes that the only partial states are measurable and uses observers at the local subsystems. The event-triggering is based on observed states and not on exact measurements as required in [11].

With the above system description and notations, we define following theorem that can be used to design the distributed output based observer and controller.

Theorem 4.1 *Consider the Distributed Networked Control System represented by (4.7), (4.9), and (4.11). Given $\gamma \in R^+, \alpha \in R^+$, assume that there exist positive-definite block-diagonal matrices $S, M, R, X_1, X_3, X_8, X_9, Y_1, Y_2 \in R^{nN\times nN}$, $X_4, X_5 \in R^{b_2\times a_1}$, and $X_2 \in R^{b_2\times b1}$ such that:*

$$\begin{bmatrix} SA + SA^t & \Gamma \\ \bullet & -\gamma^{-2}I \end{bmatrix} \leq 0 \tag{4.12}$$

$$\begin{bmatrix} A_dM + MA_d - X_1 - X_1^t + BX_2 + X_2^tB^t & M \\ \bullet & -R \end{bmatrix} \leq 0 \tag{4.13}$$

$$\begin{bmatrix} X_8 & M \\ \bullet & -I \end{bmatrix} \leq 0, \quad X_9 - \alpha X_8 \leq 0 \tag{4.14}$$

$$\begin{bmatrix} -Y_1 & BX_4 + BX_5 + X_3^t & -BX_s & \Gamma \\ \bullet & -Y_2 & -BX_8 + X_9 & 0 \\ \bullet & \bullet & X_8 - X_9 & 0 \\ \bullet & \bullet & \bullet & -\gamma^{-2} I \end{bmatrix} \leq 0 \tag{4.15}$$

$$|e(t)|_2 \leq \alpha |\hat{x}(t)|_2 \tag{4.16}$$

where, $\alpha > 0$ is the tuning variable satisfying the event-triggering condition for stable operation for all $i \in N$ and all $t \geq t_0$.
Given A, B, C, Γ, and $\alpha > 0$, the LMIs of 4.1 can be solved by existing LMI solvers to design K_l, K_n, and L for an output based event triggered controller scheme.

Proof: Consider the Lyapunov function $V = x^t P x + \tilde{x}^t P_0 \tilde{x}$. Along the trajectories of 4.9 and 4.12, we get

$$\begin{aligned} \dot{V} &= x^t P \dot{x} + \dot{x}^t P x + \tilde{x}^t P_0 \dot{\tilde{x}} + \dot{\tilde{x}}^t P_0 \tilde{x} \\ &= x^t P (Ax + Bu + \Gamma w) + (Ax + Bu + \Gamma w)^t P x \\ &+ \tilde{x}^t P_0 (A_d \tilde{x} + Bu + L[y - \tilde{y}]) \\ &+ (A_d \tilde{x} + Bu + L[y - \tilde{y}])^t P_0 \tilde{x} \end{aligned} \tag{4.17}$$

Let an error $e_i = [t_0, \infty) \rightarrow R^n$ be defined as $e_i(t) \triangleq \tilde{x}_i(t) - \hat{x}_i(t)$ for $\forall t \geq t_0$. This represents error between system i's current state estimate and its last transmitted value $e = \tilde{x} - \hat{x} \Rightarrow \hat{x} = \tilde{x} - e$. The control signal is given by,

$$\begin{aligned} u &= K_l\tilde{x} + K_n\hat{x} = K_l\tilde{x} + K_n(\tilde{x} - e) \\ &= (K_l + K_n)\tilde{x} - K_n e \end{aligned} \tag{4.18}$$

Thus from (4.17), we get

$$\begin{aligned} \dot{V} &= x^t P(Ax + BK\tilde{x} - BK_n e + \Gamma w) \\ &+ (Ax + BK\tilde{x} - BK_n e + \Gamma w)^t Px \\ &+ \tilde{x}^t P_0(A_d\tilde{x} + BK\tilde{x} - BK_n e + LCx - LC\tilde{x}) \\ &+ (A_d\tilde{x} + BK\tilde{x} - BK_n e + LCx - LC\tilde{x})^t P_0\tilde{x} \end{aligned} \tag{4.19}$$

Using following event-condition based inequality $\|e\| \leq \alpha\|\hat{x}\|,\ \alpha > 0$ and manipulating, the Lyapunov derivative can be written as

$$\begin{aligned} \dot{V} &\leq x^t[PA + A^tP + \gamma^{-2}PCC^tP]x \\ &+ \tilde{x}^t[P_0(A_d + BK - LC) + (A_d^t + K^tB^t - C^tL^t)P_0]\tilde{x} \\ &+ w^t\Gamma Px + \gamma^{-2}w^tw \\ &+ x^t(PBK + C^tL^tP_0)\tilde{x} - x^tPBK_n e + x^tP\Gamma w \\ &+ +\tilde{x}^t(K^tB^tP + P_0LC)x - \tilde{x}^tP_0BK_n e \\ &- e^tK_n^tB^tPx - e^tK_n^tB^tP_0\tilde{x} + e^te - \alpha\hat{x}^t\hat{x} \end{aligned} \tag{4.20}$$

With, $\hat{x} = \tilde{x} - e$, we now express $-\alpha\hat{x}^t\hat{x}$ as $-\alpha\hat{x}^t\hat{x} = -\alpha\tilde{x}^t\tilde{x} + \alpha\tilde{x}^t e + \alpha e^t\tilde{x} - \alpha e^t e$. Substituting back into (4.20), we get:

$$
\begin{aligned}
\dot{V} \;&\leq\; x^t[PA + A^tP + \gamma^{-2}PCC^tP]x \\
&+\; x^t(PBK + C^tL^tP_0)\tilde{x} - x^tPBK_ne + x^tP\Gamma w \\
&+\; \tilde{x}^t[P_0(a_d + BK - LC) + (A_d^t + K^tB^t - C^tL^t)P_0]\tilde{x} \\
&+\; \tilde{x}^t(K^tB^tP + P_0LC)x - \tilde{x}^tP_0BK_ne - \alpha\tilde{x}^t\tilde{x} + \alpha\tilde{x}^te \\
&-\; e^tK_n^tB^tPx - e^tK_n^tB^tP_0\tilde{x} + \alpha e^t\tilde{x} - \alpha e^te \\
&+\; w^t\Gamma Px + \gamma^{-2}w^tw + e^te
\end{aligned}
\tag{4.21}
$$

This can be written into the compact form:

$$
\begin{aligned}
&\dot{V} \leq \zeta^t\Xi\zeta, \quad \zeta = [x^t, \quad \tilde{x}^t, \quad e^t, \quad w^t]^t, \\
&\Xi = \begin{bmatrix} \Xi_o & PBK + C^tL^tP_0 & -PBK_n & P\Gamma \\ \bullet & \Xi_a & -P_0BK_n + \alpha I & 0 \\ \bullet & \bullet & (1-\alpha)I & 0 \\ \bullet & \bullet & \bullet & \gamma^{-2}I \end{bmatrix} \\
&\Xi_o = PA + A^tP + \gamma^{-2}PCC^tP \\
&\Xi_a = P_0(A_d + BK - Lc)(A_d^t + K^tB^t - C^tL^t)P_0 - \alpha I
\end{aligned}
\tag{4.22}
$$

where $\bullet$ stands for symmetric terms. A sufficient condition for stability is that $\dot{V} \leq 0$ which in turn is guaranteed by $\Xi \leq 0$. Now, let $PA + A^tP + \gamma^{-2}PCC^tP = -Q_1$, and $P_0(A_d + BK - LC)(A_d^t + K^tB^t - C^tL^t)P_0 = -R_1$, then Ξ can be written as

$$\Xi = \begin{bmatrix} -Q_1 & PBK + C^t L^t P_0 & -PBK_n & P\Gamma \\ \bullet & -R_1 - \alpha I & -P_0 BK_n + \alpha I & 0 \\ \bullet & \bullet & -(\alpha - 1)I & 0 \\ \bullet & \bullet & \bullet & -\gamma^{-2} I \end{bmatrix}$$
$$\leq 0 \tag{4.23}$$

Letting $S = P^{-1}, M = P_0^{-1}, Y_1 = SQS, Y_2 = M(R_1 + \alpha I)M, X_1 = LCM, X_2 = KM$, we express the first two diagonal blocks of Ξ as

$$\begin{bmatrix} Y_1 + AS + SA^t & C \\ \bullet & -\gamma^{-2} I \end{bmatrix} \leq 0$$
$$\begin{bmatrix} Y_o & M \\ \bullet & -R_1 \end{bmatrix} \leq 0$$
$$Y_o = Y_2 + A_d M + BKM - LCM + MA_d^t$$
$$+ MK^t B^t - MC^t L^t$$

Now, by change of variables, let $X_1 = LCM$, and $X_2 = KM$, we have $L = X_1 M^{-1} C^t$ and $K = X_2 M^{-1}$. Therefore, the LMI can be written as

$$\begin{bmatrix} A_d M + MA_d^t - X_1 - X_1^t + BX_2 + X_2^t B^t & M \\ * & -R \end{bmatrix} \leq 0 \tag{4.24}$$

By making change of variables $X_3^t = SC^tL^t, X_4 = K_1M, X_5 = K_nM$ and using congruent transformation, $W = diag[P^{-1}, P_0^{-1}, P_0^{-1}, I]$, we cast $W^t\Xi W \leq 0$ into the form:

$$\begin{bmatrix} -Y_1 & BX_4 + BX_5 + X_3^t & -BX_s & \Gamma \\ \bullet & -Y_2 & -BX_5 + \alpha X_8 & 0 \\ \bullet & \bullet & (1-\alpha)X_8 & 0 \\ \bullet & \bullet & \bullet & -\gamma^{-2}I \end{bmatrix} \leq 0$$

where $MM = X_8$ and letting $\alpha X_8 = X_9$. These constraints can be incorporated as two additional inequalities:

$$X_9 - \alpha X_8 \leq 0$$
$$\begin{bmatrix} X_8 & M \\ M & -I \end{bmatrix} \leq 0$$

Grouping the foregoing inequalities leads to the LMIs (4.12)-(4.16) as desired.

Remark 4.4.2 *These LMIs can be solved by the existing LMI solvers to get find feasible solutions for LMI variables for an appropriate α. Once get the feasible solution of these LMI variables, we can find the observer gain matrix L and the controller gain matrices K_l, and K_n.*

Remark 4.4.3 *The Theorem 4.1 can be used to tune the threshold parameter α. The LMIs can be solved for individual subsystem for a range of α_i for individual subsystem i, and a combined objective function based on α_i can be used to* *individually tune the value of α_i at individual subsystem in distributed networked systems. This way, distributed event triggering can be achieved according to the varying (slow to fast) dynamics of the individual subsystem.*

4.5 Simulation Result

This section presents the numerical solution and simulation results for a collection of coupled carts taken from [38]. This example illustrates three carts coupled by springs. We assume that each cart is equipped with individual observers and local control is calculated based on local observed states and on the information received from network. The individual subsystem (i.e., the ith cart) has state vector $\dot{x} = [p_i v_i]^t$, where p_i is the position, and v_i is the velocity of ith cart. At equilibrium, the coupling springs are assumed upstretched. Dynamic equation for ith cart is $\dot{x} = A_i x_i + B_i u_i + H_{i,i-1} x_{i-1} + H_{i,i+1} x_{i+1}$, where $A_i = \begin{pmatrix} 0 & 1 \\ -\mu_i k & 0 \end{pmatrix}$, $B_i = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, and $H_{ij} = \begin{pmatrix} 0 & 0 \\ \nu_{ij} & 0 \end{pmatrix}$.

The system parameters are (see [38]): N=3, spring constant $k = 5$, $\mu_1 = \mu_N = 1$, $\mu_2 =$. For coupling, $\nu_{ij} = 1$ for $i \notin 1, N$, $j \in i-1, i+1$, and $\nu_{12} = \nu_{N,N-1} = 1$, otherwise $\nu_{ij} = 0$. The overall model is described by following matrices:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -5 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & -5 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \; D = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

With $\alpha = 0.5$, the LMI solver returns feasible solutions with following LMI variables $\gamma = 1.3782$

$$L = \begin{bmatrix} -3192.1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -3192.1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -3192.1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$K_l = \begin{bmatrix} 0 & 2.8648 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.8602 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.8556 \end{bmatrix},$$

$$K_n = \begin{bmatrix} 0 & -1.0885 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1.0867 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1.0850 \end{bmatrix}$$

The simulation graphs of the considered example show the stable closed loop performance. Using the LMI Solver, the feasible solution resulted in following trajectories. Plant states, control inputs and plant outputs are shown in Figs. 4.2, 4.3, and 4.4 respectively. The observer states, corresponding outputs are shown in Figs. 4.5, and 4.6 respectively. Absolute error between the plant output and the estimated output is shown in Fig. 4.7. Smooth behavior is observed which showed the effectiveness of the developed approach.

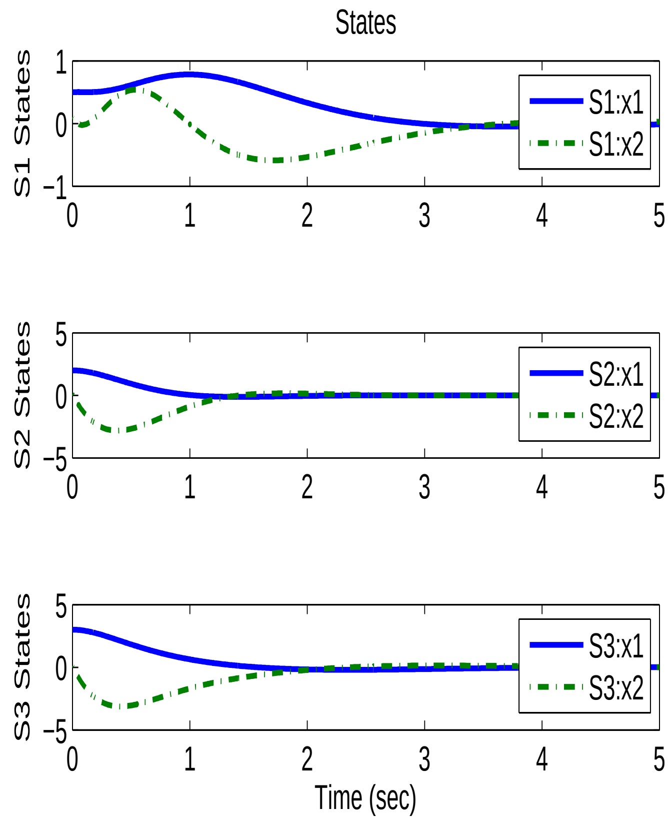

Figure 4.2: Plant state trajectories

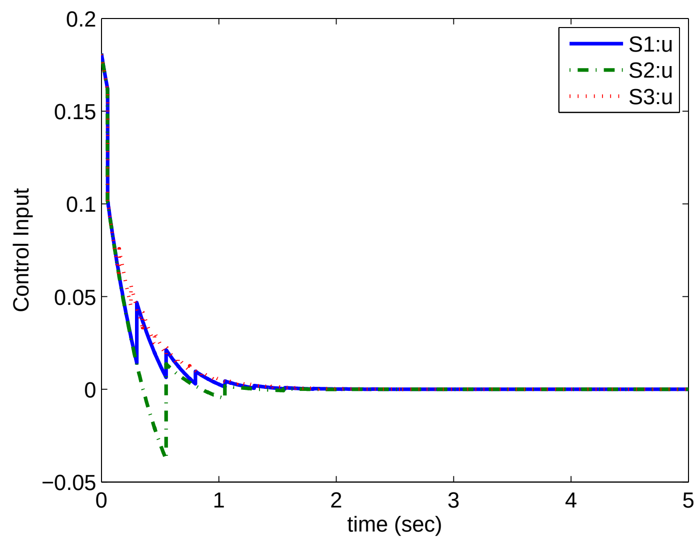

Figure 4.3: Behavior of control inputs

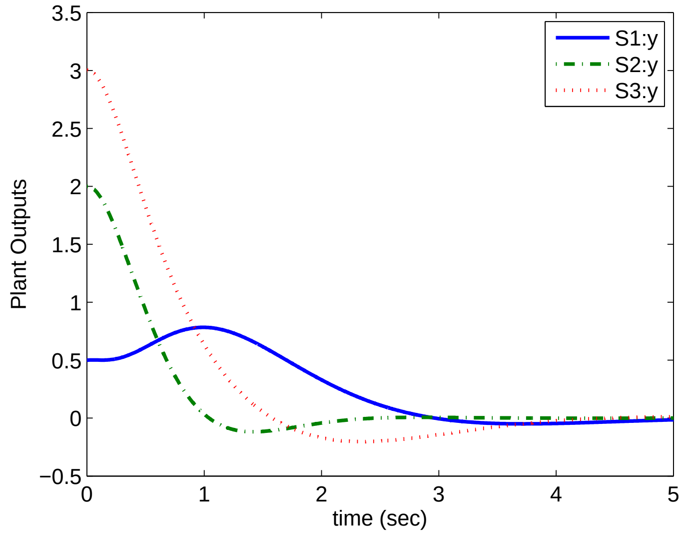

Figure 4.4: Plant output patterns

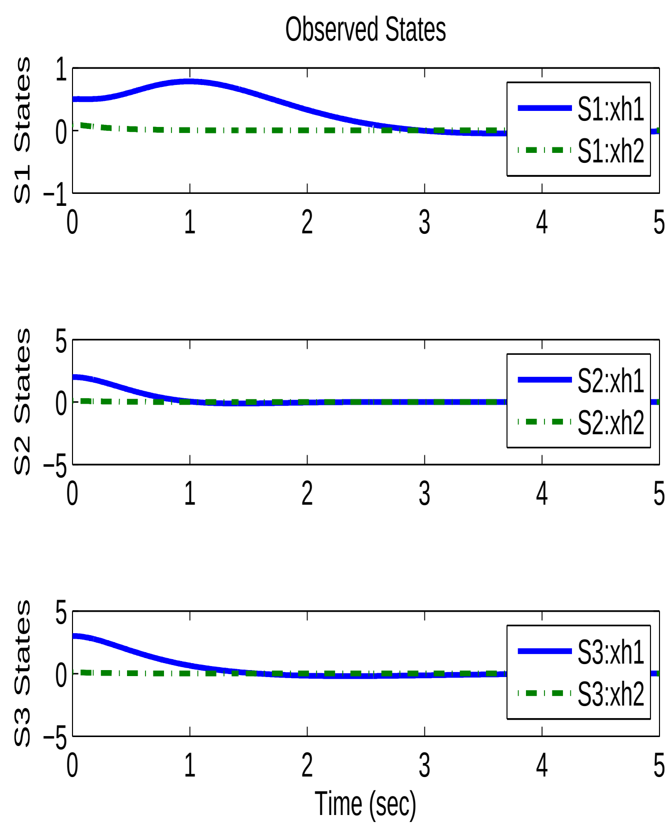

Figure 4.5: Observer state trajectories

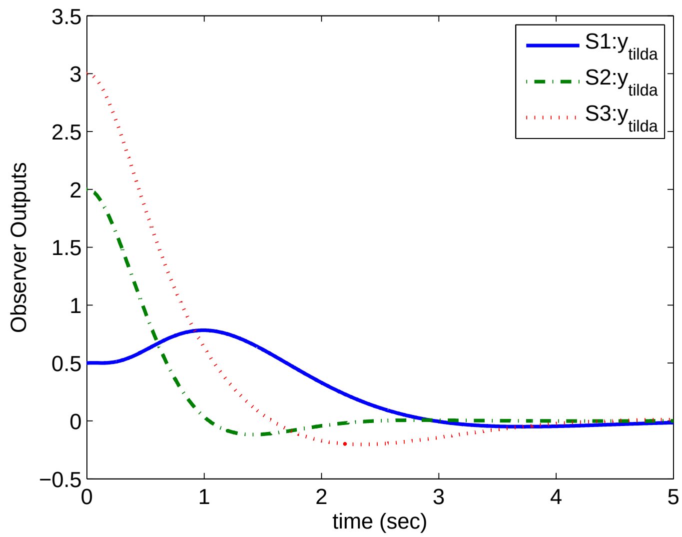

Figure 4.6: Observer output trajectories

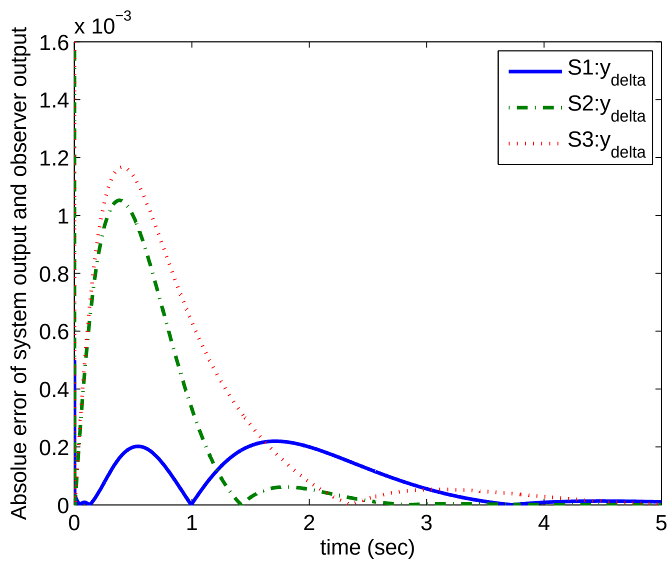

Figure 4.7: Output error of system and observer outputs

4.6 Conclusions and Future Work

The problem of event-triggered output-feedback control is solved in the context of distributed networked control systems. The problem is solved in terms of a linear matrix inequality (LMI) feasibility solution. The output based controller is designed based on the local observed dynamics and the information shared by neighboring interacting subsystems. The information sharing is based on an event condition which requires only locally observed dynamics. The control law is designed in two parts to take care of individual dynamics as well as the coupling of the subsystems. The proposed design is illustrate by using a benchmark example of a batch reactor which shows the stabilizing results of the control system.

Current work is focused on developing stable event-triggered output-feedback control algorithm for distributed networked systems. This work can be extended to search of optimal bounds for the distributed event triggering scheme in the presented output based framework. Study of the distributed observers including scheduling methods also has a research potential. The work can be further be extended to address self-triggered control and co-design methods in the framework of distributed networked systems.

CHAPTER 5

EVENT-TRIGGERED VERSUS TIME-TRIGGERED NETWORKED SYSTEMS

This chapter presents the study and evaluation of the Time-Triggered Control (TTC) and Event-Triggered Control (ETC) in view of Distributed Networked Control Systems (DNCS) over wireless network. Besides the guaranteed use of time-triggered control system, it has been shown that Event-triggered control results in large reduction in computational and communication resources while keeping control performance at reasonable level. Going for faster time-triggered (i.e., periodic) systems is not the optimal and practical choice in case of distributed networked systems, where synchronization and multi-rate sampling is an issue. An alternate approach is event based scheme that is resource efficient. This chapter investigates the control performance of time-triggered and event-triggered control system using simulation examples and related analytical discussions. A set-point tracking example consisting of sensor with send-on-delta triggering and event triggered PI controller is studied in the PiccSIM (a co-simulation environment based on Simulink and Network Simulator NS-2). A second simulation is done for a stabilizing example of a three cart system which is simulated in TrueTime (Matlab based network control simulation package) to demonstrate the comparison for distributed networked systems.

5.1 Introduction

The current control engineering practice assumes the periodic sampling and control for sensors, controllers and actuators. The sampling period can vary depending upon the sensors and controlling device and multi-rate sampling is usually observed in a practical process plant. But, the time-triggered nature of the overall automatic control theory is assumed as default. One of the reasons is the wide spread development and common use of control theory for sampled data system, e.g., [127]. Recently due to technology push of communication, physically interconnected systems, and the requirement of resource optimization, leads the researchers to think about alternate solution. One solution of resource optimization is to use them efficiently, i.e., use the resource while ensuring a good enough performance. The resource optimization and improved control performance offer a tradeoff and can vary with application and criticality of situation.

Event based (aperiodic or asynchronous) control system is the most prominent alternative to time based control systems showing the potential for future control applications specially in wireless based monitoring and control applications. Among several application areas, the distributed networked control system (DNCS) is the most attractive and promising area for event based communication and control methods. DNCS can be treated as a class of cyber-physical system. It is interesting to note that some physical systems are inherently based on event based sampling. In such systems, properly designed event based control can definitely outperform the time triggered methods. An example of this is an internal combustion engine, where control action is based on sampling against engine speed. Other systems like supply & chain and manufacturing production systems are better designed when based on demand rate.

5.1.1 Research directions in ETC

Currently, researchers are looking for ways to provide quantitative assessments and comparisons of cases when ETC can outperform, compete or efficiently approximates TTC. We use the term "efficient-approximation" to highlight the cases when ETC can compete or approximate in control performance while outperform TTC in utilizing resources. There are three general research areas for event based systems to be developed, (1) theoretical results, (2) Practical validation, and (3) Comparison with TTC. Besides developing the theoretical results and practical validation, this is also important to figure out quantitative ways highlighting performance tradeoff between event-triggered and time-triggered methods. From control engineering aspect, such quantitative method should account for both control cost and networked communication cost. Such cost based functions can be used to assess overall control performance and also help in the co-design approach for networked based control systems. These cost functions and control performance indexes are discussed in 5.3. Comparison investigations can help to identify the cases in which event-triggered methods of communication and control are advantageous than time-triggered methods specially in case of Distributed Networked Control Systems.

5.1.2 Why consider ETC in distributed networked systems

For a distributed networked system, the large number of networked sensors, actuators and controllers may result in high data traffic requiring high bandwidth networks. Even in high bandwidth networks, the delay and dropout may bring the overall system under stability and performance threats. Having high specifications network is also not feasible in case of every control loop. The situation becomes computationally and energy wise expensive when wireless network is used between sensors, actuators and controllers as the communication channel.

Due to the synchronization and communication issues in distributed systems, Event based scheduling, estimation and control offer potential benefits over time based estimation and control techniques. Recall that event based systems are intelligent system in the sense that they make decisions against some piece of information rather than blindly repeating its function with the time clock. The remainder of this chapter is organized as follows. Section 5.2 discusses the related event triggered work in distributed networked systems, wireless based systems and shows graphical comparison of event triggered and time triggered control from the literature. The event based distributed framework used to study and evaluate the performance of event-triggered and time-triggered control is described in Chapter 4. Section 5.3 discusses the ways of comparing the time triggered and event triggered schemes from networked system aspect. Section 5.4 highlights the control and communication performance of the simulated examples developed in TrueTime and PiccSIM. Section 6 provides some final conclusions.

5.2 Related Work

Initial comparative study appeared in [14] where these two methods are compared in view of closed loop variance and average sampling rate. Although majority of the work on event triggered control is focused on single control loop, there are some studies for multiple feedback loops in the presence of physically distributed sensors and actuators.

5.2.1 Distributed networked systems

Consensus problems are the first issues in a distributed system. In case of distributed monitoring system, consensus problem include sensor fusion, while in distributed control techniques, the connectivity of the distributed control agents is crucial. In either case, the connectivity of sensors or the control agents is the key to develop a convergent method. In [44], a solution to the problem of algebraic connectivity is proposed in event-triggered consensus. The algebraic connectivity of a graph is the second smallest eigenvalue of the Laplacian matrix of the graph. If the eigenvalue is greater than 0, then the graph is connected. Larger eigenvalue reflects well connected graph. Algebraic connectivity if used to analyze the synchronization and robustness of the overall network. The method allows agents to estimate the algebraic connectivity at each step in parallel with the matrix power algorithm in event-triggered scenario. The distributed estimation algorithm for the algebraic connectivity depends on the distributed computation of the powers of matrices. The estimation of connectivity bounds in [44], can be combined with other distributed algorithms for adaptive consensus in a parallel fashion. In [45] a distributed event-triggered control for multi-agent systems is discussed. Event-driven strategies for multi-agent systems are motivated by the future use of embedded microprocessors with limited resources that will gather information and actuate the individual agent controller updates. The controller updates considered here are event-driven, depending on the ratio of a certain measurement error with respect to the norm of a function of the state, and are applied to a first order agreement problem. A centralized formulation is considered first and then its distributed counterpart, in which agents require knowledge only of their neighbors states for the controller implementation. The results are then extended to a self-triggered setup, where each agent computes its next update time at the previous one, without having to keep track of the state error that triggers the actuation between two consecutive update instants. The work in [45] can be extended to the performance analysis of the framework and its application to other cooperative multi-agent control tasks. Since in [45], reduction of control update is emphasized, a natural extension of [45] is to investigate sensing limitations. Recently, event based methods are also studied for advanced control techniques, for example, in [46] event-based model predictive control for the cooperation of distributed agents is investigated. [46] presented an event-based framework for the control of a team of dynamically coupled distributed agents. These agents are controlled locally by Nonlinear Model Predictive Controllers (NMPC). The optimal solution is sought for MPC only at event triggers. Distributed event-based control strategy for a networked dynamical system is studied in [47] linear interconnected systems. Triggering rules of subsystems to broadcast are based on local information only. Convergence properties and lower bound on broadcasting period is provided. The number of events are reduced by using a model based approach. The framework of [47] is extended to network delays and packet losses in [48]. To deal with the network issues on delay and packet loss, two communication protocols are proposed to ensure the stability of the linear distributed system. These protocols preserve a bounded stability near to a small region around the origin. Such bounds on delay and packet losses are derived analytical for the two proposed communication protocols. Distributed event-triggered tracking control of leader-follower multi-agent systems with communication delays is investigated in [49]. Key motivation of event based approaches for distributed system is due to the usage of embedded processors in distributed systems where energy and computational resources are limited or at least not abundant. The stability of the tracking control multi-agent system is ensured by an ISS Lyapunov function. In [50] function block automation standards, i.e., IEC 61499 and IEEE 1588 are investigated for time-complemented event-driven distributed control. Initial study is provided for the applications of IEC 61499 Function Block standard in distributed motion control systems, where synchronization is of crucial importance. In particular, an investigation on the possibilities of applying event-driven function blocks in the time-based motion control system has been performed on the SIDEL SL90 packaging machines control system. In [51], distributed event-triggered sampling scheme for controlling interconnected systems is presented. The individual subsystems in the interconnection decide the triggering independent to other subsystems. Such decision is based only on the subsystem's state and a Lyapunov function. Stability condition of the overall system is developed on small-gain theorem. Event-triggered and self-triggered stabilizing control is studied in [52] The framework of [53] which is developed for sampled-data systems is extended in [52] to develop event-triggering rules for distributed networked control systems. The self-triggering conditions are derived by applying the techniques of [54]. Scheduling of the distributed actuators and sensors is the fundamental question in a distributed networked control system is [52]. The distributed framework of [52] can be extended to design communication protocols for event triggering conditions on information sharing between distributed nodes. Distributed Network Utility Maximization (NUM) using Event-triggered Barrier Methods is investigated in [55]. In [11] event-triggered data transmission in distributed networked control systems with packet loss and transmission delays is investigated. In this distributed event-triggering scheme, a subsystem broadcasts its state information only when the local state error exceeds a threshold value. For nonlinear subsystems, the local event design is transformed into local ISS design problems; for linear subsystems, the design is simplified to be local linear matrix inequality (LMI) feasibility problems. With the assumption that the transmission delay is zero and the number of each agents successive data dropouts is less than its MANSD, the resulting NCS is shown as finite-gain L_p stable. When the transmission delay is not zero, state-based deadlines are provided that are always greater than a positive constant. As long as the delay in each transmission is less than the associated deadline, the resulting NCS is asymptotically stable, provided the external disturbance vanishes. In [56] event-triggered broadcasting across Distributed Networked Control Systems is studied in presence of wireless communication networks. Broadcasts are decentralized and based on the individual subsystem's measured states. Information from the neighborhood is used to adjust the event-triggering level. This way, a subsystem can adjust its broadcast rate in view of the amount of activity in its immediate neighborhood. The work in [56] is further extended in [38] with investigation of distributed networked systems in case of data dropouts and transmission delays. Distributed optimization in event triggered framework is investigated in

[57] for sensor networks. An event-triggered distributed algorithm is proposed for the data gathering problem and the convergence is discussed. It is shown that the algorithm reduced the number of message exchanges as compared to the alternate dual decomposition algorithms. Distributed event-triggered estimation over wireless sensor networks is also studied in [58]. This estimation algorithm performs distributed estimation of networked systems when sensor measurements are transmitted over a wireless sensor network. Passivity-based I/O approach for stabilization of large scale networked control systems (NCSs) with event-driven communication is studied in [59]. A cellular model is used to represent the large scale NCSs and it is assumed that each subsystem is an output feedback passive (OFP) system. Here also, the communication strategy of broadcasting information depends on local output error against a threshold. Finite-gain L2 stability is analyzed in the presence of bounded external disturbances.

5.2.2 Wireless based systems

Advancement in Wireless technology has motivated control researchers to study the control over wireless channels due to its many benefits. Key benefits of a wireless device, (sensor, actuator or controller from a control engineer's aspect), include installation at difficult places, mobile operation, reconfigurability, multipath (like mesh) networks , no installation of wires, etc. Wireless based solutions are studied and offered with different names like Wireless Automation, Wireless Sensor/Actuator Networks, and Wireless Sensor Networks for monitoring and control applications. The future is undoubtedly in favor of wireless based solutions. The shared communication channels (i.e., open air medium), battery operated wireless nodes, and low computational power at nodes, offer challenging sensing and control schemes for wireless control systems. Such constraints on resources encourage and make Event based techniques, natural choice of operation in wireless control systems. Therefore, in this section, recent literature on event triggered control for wireless systems is presented. In [37] a decentralized scheme for event triggered control over wireless sensor/actuator network (WSAN) with low computational requirement is presented. Commonly the wireless channel is used for monitoring applications, while the aim is to use wireless actuators to close the feedback loop over wireless [37]. By using event triggering in wireless, the number of control computations, and sensor transmission are reduced. This leads to energy efficient control loops with satisfactory performance. Compared to [38], where a method is proposed for distributed event-triggered control for weakly coupled subsystems, approach in [37] does not require weakly coupled subsystems. The decentralized technique is tested on a four-tank system. This work can be further extended to general dynamic controller in event triggered implementation and to design adaptation rules for flexible implementation. Output feedback in event triggered control has been studied by few researchers only. For example, in [39], the output feedback of wireless networked control systems is studied. The communication links, between sensor to controller and from controller to actuator, are treated separately. Based on assumption of weakly coupled subsystems, the triggering depends on local information. This way, the sensor and controller's event-triggers are not required to be synchronized. A good discussion on event based sampling over wireless networks can be found in [40]. As first step to develop theory for event based control, classical control techniques like PID and minimum variance control are extended to event triggered control, for example, [40], [22], and [15]. In such extensions, an additional activity includes the design of event detector for the best aperiodic sampling. In [41], wireless based event triggered control has been investigated on an experimental setup. The work in [41] investigated an event triggered design and implementation for a nonlinear 3D tower crane. An Event-Generation Circuit (EGC) is also demonstrated to flexibly implement event-driven controllers in networked systems. Two fold benefits of event triggering for wireless include extended lifetime of sensor nodes and reduced network traffic. Performance studies are also presented in [41] of the event triggered control and the time triggered control in presence of disturbance, delay and packet loss. Although resulting event triggered method shows similar performance performance with much reduced communication, it does not provide guarantee of stability. There can be several interesting future extensions to the research presented in [41], including general reference tracking, conditions on stability, and decentralized event-triggered control. A co-design approach is proposed in [42] to modify the IEEE 802.15.4 MAC standard to implement event-triggered control over wireless sensor and actuator networks. Based on [42], the problems in event triggered wireless control can be stated as : (1) Find triggering condition for sensor and controller ensuring stability and desired performance while minimizing the energy utilization at wireless nodes.

(2) Design and implement the event based sensing and control strategy using off-the-shelf technology with satisfactory performance and stable control loops. In [43], an event-based technique for distributed estimation over wireless sensor networks (WNSs) is studied. Local Luenberger based observers are used with a consensus strategy for distributed estimation. The observer is designed in time triggered scenario using linear matrix inequalities, then an eventbased strategy is proposed to reduce communication and energy consumption of the nodes. The work in [43] does not consider packet loss and delay, thus a natural extension will be investigation of packet dropouts and time delays. Further, [43] can be extended for more general distributed observers and distributed controllers for wireless based event triggered framework. Event-based control has potential to be used in wireless networked control systems. Event based schemes can help to achieve efficient use of network resources while fulfilling the required control objectives. Also, the stochastic control approach for event based systems is natural to be investigated because of the probabilistic nature of wireless channel. Research on wireless based event triggered control will lead to new research questions including multi-loop systems and multi-hop networks. What industry will like is investigation of control techniques over mesh-wireless networks.

5.2.3 Examples of comparison from literature

Event triggered control can be beneficial in following two ways. In first case the Event-Triggered control can outperform time-triggered Control when the average sampling of the two techniques is made equal. In second case the Event-triggered control is demonstrated to use communication resources more efficiently as compared to time-triggered control while the control performances of the two are similar.

Case 1: Event-Triggered control outperform time-triggered Control on average sampling basis

A comparison plot for a scalar diffusion process (5.1) is shown in Fig. 5.1 [22].

$$dx = axdt + udt + dw \tag{5.1}$$

where a is a real constant and w is a standard Brownian motion. The control signal u is calculated by time-triggered and event-triggered methods. During the event-triggering condition, the control is computed when state exceeds a specified threshold. In [22], the control performance is evaluated by the steady-state variance of the system state. In Fig. 5.1, V_L is the variance under event-triggered sampling, and V_R is the variance under periodic sampling. The performance ratio V_R/V_L is calculated as a function of mean sampling period (T). This performance ratio in Fig. 5.1 is greater than one for all choices of system constant a, thus indicating that the event triggered system perform better than periodically triggered system provided same mean sampling period.

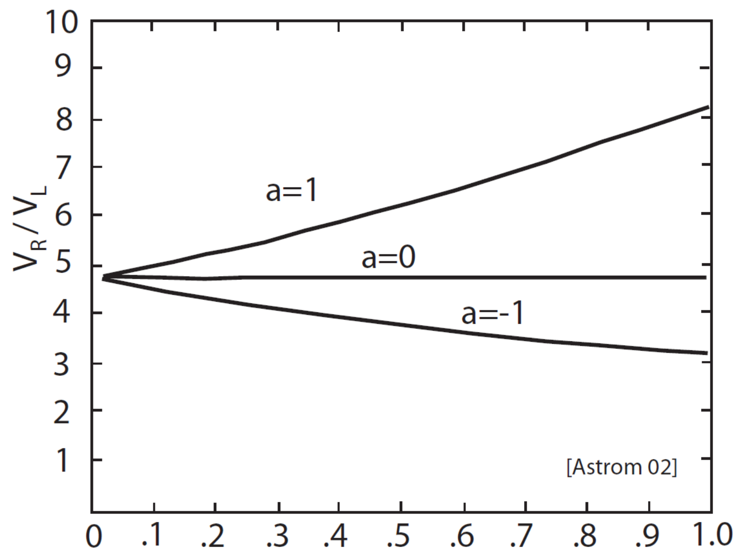

Figure 5.1: Performance Ratio vs. Mean Sample Period (T) [25]

Case 2: Event-triggered control uses communication resources efficiently as compared to time-triggered control for similar performance levels

Another example (Fig. 5.2) from literature [73] highlights the efficiency of event triggered scheme in terms of computations resources. The top plot in Fig. 5.2 shows tracking error in case of time-triggered PID of a linear plant. The error for an event-triggered PID based on a triggering condition given in 5.2 is shown in the middle plot of Fig. 5.2. In case of event-trigger PID, control is calculated when the difference of current state $x(t)$ and the last sampled state $x(r_j)$ (say at time j) exceeds a threshold e_T.

$$|e(t)| = |x(t) - x(r_j)| \leq e_T = threshold \tag{5.2}$$

The last plot in Fig. 5.2 shows the number of samples in case of time-triggered and event-triggered control schemes. This example and related plots in Fig. 5.2 demonstrates that the event-triggered controls scheme require less number of feedback signals and control signal calculations with approximately similar performance to equivalent time-triggered control scheme.

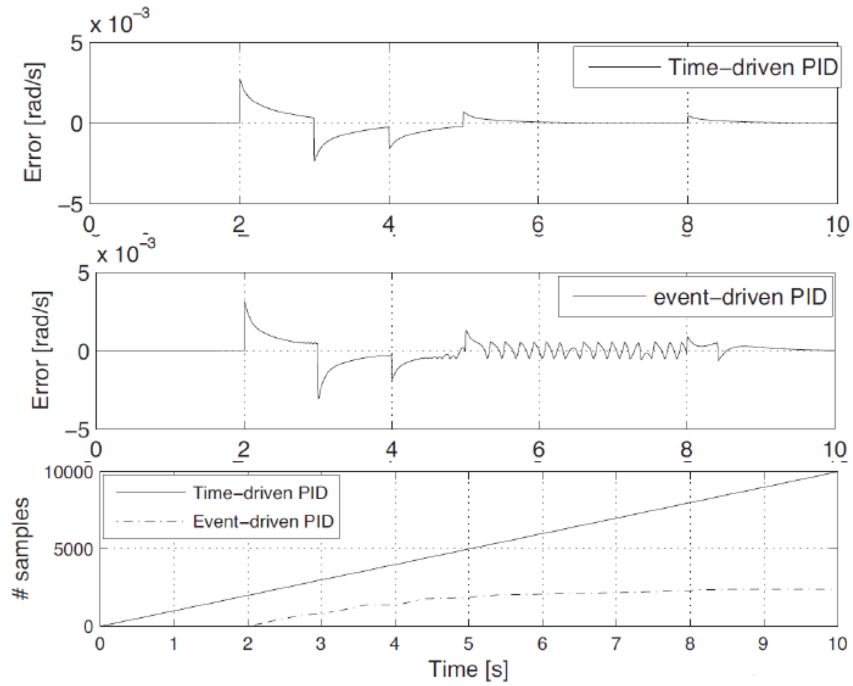

Figure 5.2: Tracking error and sampling for event-triggered and time-triggered control [30]

5.3 Comparing Time-triggered and Event triggered control

The sampling for event triggered control and time triggered control are different. Time triggered sampling is Riemann sampling which is a function of time. In order to capture the dynamics of a signal or system, the time period is chosen based on Shannon Sampling Theorem, i.e., the sampling should be twice the highest frequency in the system dynamics. While, in event triggered sampling (which is called Lebesgue sampling), the sampling is aperiodic and is not a function of time, instead it may be a function of amplitude or rate of change of some states of the dynamical system.

Thus the comparison of TT and ET is not straight forward. In order to compare the time triggered and event triggered, following ways can be used:

- using same framework to represent time-triggered control (i.e., sampled-data control), and the event-triggered control (ETC)
- using performance criteria based on error bound, tracking, and disturbance rejection
- using some utilization index (i.e., how much resources are utilized in either methods)
- using trade-off between control performance and communication utilization
- using implementation benefits in either control methods

In the following lines, we discuss some of these ways to complete the picture. We have used control performance along with communication resource utilization to judge the two techniques.

5.3.1 Performance measurement factors

Networked control systems should be designed by taking into account the control performance as well as the communication performance. For that purpose, the overall performance measurement factor should reflect cost function from control and communication aspect. Usually the control costs are quadratic costs as in LQR control or relevant Lp-gains, while communication costs may include average sampling rates, minimal inter-event times, and transmission power.

This is interesting to know the difference between (1) A performance measure for observing and investigating the best of available control techniques, (2) A performance measure to optimize the available control techniques. So, a performance measure usually the mathematical function or value (e.g., integrated error) that is used to judge the performance of a control technique in some specific scenario. While, cost function is the given name of a mathematical function, which is used to optimize the control technique. In event-based networked control systems, the optimization can be achieved for control, network resource scheduling and for event design. Thus the cost function (CF) as well as the performance measure (PF) of an Event based Networked control system should reflect these three aspects. Thus, optimization of a Networked Event-Triggered Control System has three degrees of freedom that can be exploited according to applications and available resources.

5.3.2 Cost function

A cost function is the performance measure, which is minimized and can be used to compare two different control techniques. Examples of cost function include total power consumption, integrated error, and deviation from a target value. The cost function is a functional equation, which maps a set of points to a single quantitative value. So, a cost function can be used as a quantitative measure of the overall designed scheme. In networked control systems, the cost function must reflect control cost as well as communication cost, i.e.,

Cost function = Control Cost + Communication Cost

where, Control Cost may include quadratic cost (e.g., LQR), and $\mathfrak{L}_p$ gain Cost, while Communication Cost may include Average Sampling Rates, Minimum Inter-Event Times, Transmission Power. An example of the cost function consisting of the linear quadratic for the control performance and a communication cost for information exchange between the sensor and controller is given below [128]:

$$J(f, g_c) = E[x_T^T Q_T x_T + \sum_{k=0}^{T-1} x_k^T Q x_k + u_k^T R u_k + \lambda \delta_k] \tag{5.3}$$

where objective is to find the admissible policies f, and g_c, while minimizing the multi-objective criterion $J(f, g_c)$. Here, Q, and Q_T are the positive definite weighting matrices, R is positive semi-definite matrix, λ is a weighting factor for information exchange between the sensor and controller.

The analytical assessment can be done in following directions:

- Assume average sampling and compare Variance of Closed Loop Control based on [22], and [129]
- A Cost Function based taking account of Control Cost and Communication Cost

The comparison in [22] is for a single loop control system and not for networked control systems. We will first present the structure of comparison as appeared in [22], and then extend it for distributed networked control systems.

5.3.3 Control performance

Several performance measurements to compare the quality of the control for event triggered and time triggered control are the following [130]:

- IAE: The Integrated Absolute Error is defined as:

$$IAE = \int_0^\infty e(t)dt \tag{5.4}$$

- IAEP: It is the difference between the system response of an event-based strategy and the system response of the time-based approach:

$$IAEP = \int_0^\infty |y_{time-based}(t) - y_{event-based}(t)|dt \tag{5.5}$$

- NE: The Number of Events is a sampling efficiency measure to compare the quality of the system response:

$$NE = \frac{IAEP}{IAE} \tag{5.6}$$

The sampling efficiency measure can be defined then as:

$$NE = IAEP/IAE \tag{5.7}$$

and indicates the reduction of triggered events compared to the periodic sampling. Similarly, the produced event rates (number of events) are compared with the reference periodic implementation using following efficiency measure:

$$N_N = N/N_{per} \tag{5.8}$$

where N_N - normalized number of events (event efficiency measure), N - number of events produced in the loop with deadband sampling, N_{per} - number of events produced with periodic sampling.

- IAD: The integrated absolute difference is the difference between the IAE of the time-based strategy and the IAE of the event-based ones:

$$IAD = \int_0^\infty |IAE_{time-based}(t) - IAE_{event-based}(t)|dt \tag{5.9}$$

Since the sources of events influence the loop in different way, the events should be considered separately according to their source. To summarize the performance parameters regarding the event sources, the generalized performance index (PI) is introduced, which is defined similar to performance index in [131]:

$$
\begin{aligned}
PI = W_{N-SC} \cdot N_{N-SC} + W_{N-C} \cdot N_{N-C} \\
+W_{N-CA} \cdot N_{N-CA} + +W_{N-A} \cdot N_{N-A} \\
+W_E \cdot N_E
\end{aligned}
\tag{5.10}
$$

where N_{N-SC} - efficiency measure for the number of messages transmitted from sensor to controller, N_{N-C}- measure for the number of CPU calls, N_{N-CA} - efficiency measure for messages from controller to actuator, N_{N-A} - measure for the number of control actions in actuator (as a rule, $N_{N-A} = N_{N-CA}$), N_E - performance indicator (see formula 7), $W \ldots$ - weights indicating the importance of the corresponding factor.

5.4 Simulation Study

Comparison is done by using TrueTime and PiccSIM Simulation environments. Examples studied are:

- A single loop example in PiccSIM
- A DNCS Example of Event based control of Three-Cart from [11] in True-time

5.4.1 Comparison study in PiccSIM

The PiccSIM simulator

PiccSIM (Platform for Integrated Communications and Control SIMulation) is co-simulator based on MATLAB's SIMULINK and Network Simulator (NS-2) (see [132], and [133]). The simulator provides control-design in SIMULINK and network simulation in NS-2. It is intended for research on NCS or Wireless NCS (WiNCS). The overall simulator is accessed by one Graphical User Interface called Toolchain. The integrated toolchain allows to study different aspects of communication and control and suits to conduct event-triggered and self-triggered communication and control methods.

With PiccSIM both the network and control system is simulated simultaneously and the interaction between them is studied. We can model a plant in Simulink and Network in Ns-2. The simulator returns statistics of packet drops and delays from the NS-2 trace file. The good thing about the simulator is that it supports both the event based (with trigger signals) and periodic based transmission. The event driven example studied in PiccSIM uses a sensor implementation with a send-on-delta method. The sensor sends a new measurement only if the measurement differs by a certain amount from the previously sent measurement. This helps to use the bandwidth efficiently and communicates only in case of some appreciable change. The controller is also event driven and calculates new control signal only if a new measurement is received. The controller is a PI controller. The integral action takes into account the time since last control calculation. The process model in this example is given below:

$$G(s) = \frac{1}{s+1}e^{-0.2s}$$

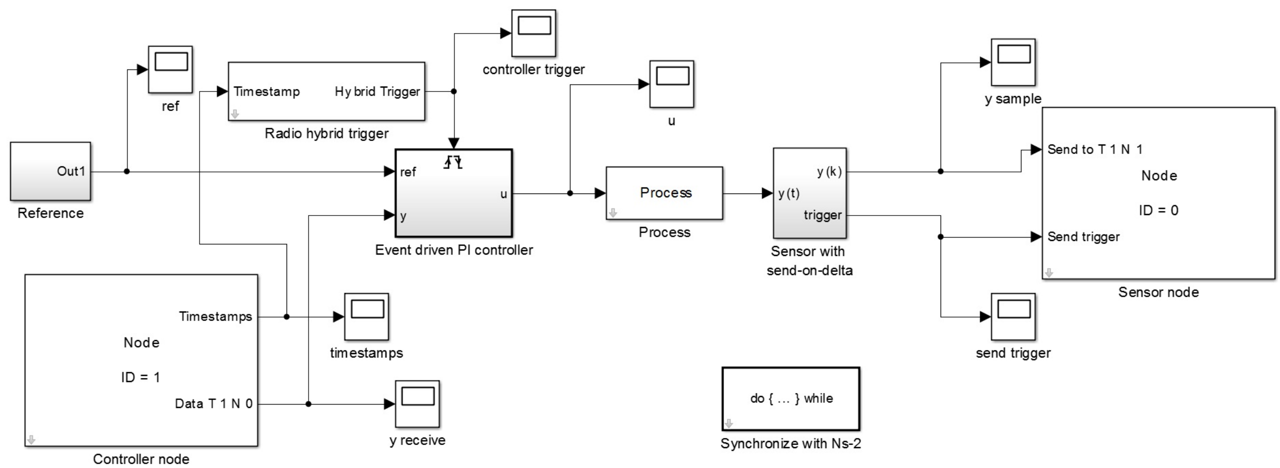

Figure 5.3: Simulink Block Diagram of the example from PiccSIM

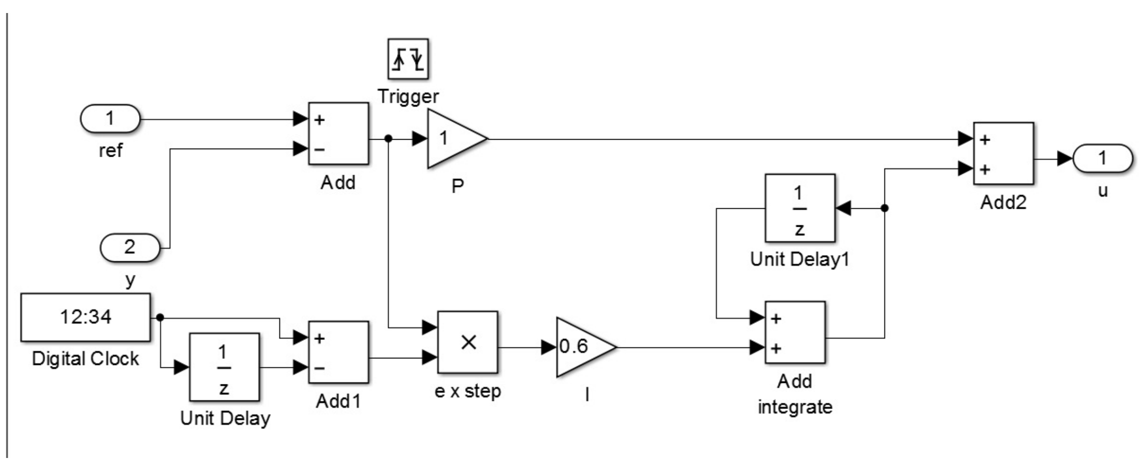

Figure 5.4: Event Triggered PI Controller

Fig. 5.3 shows the Simulink Block Diagram of the Example simulated in PiccSIM. Fig. 5.4 shows the Event Triggered PI Controller and the sensor block with triggering mechanism is shown in Fig. 5.5. Fig. 5.6 shows the monotonically

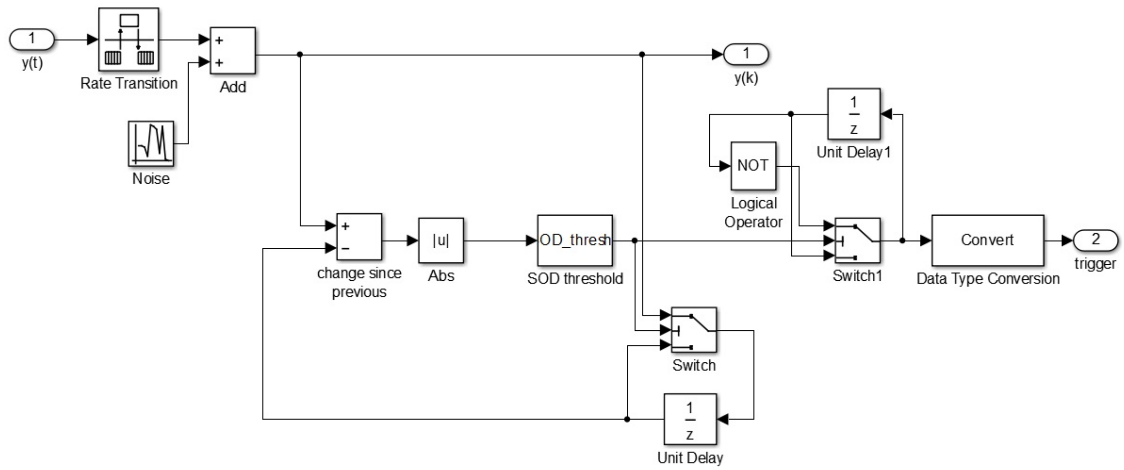

Figure 5.5: Sensor block with send-on-delta mechanism

increasing Timestamps for the cases of time-triggered and event triggered control. Notice that in case of event-triggered control, the timestamps take constant value for some larger duration as compared to time-triggered timestamps. Fig. 5.8 shows the control signals of the two cases. Fig. 5.10 shows the output signal of time-triggered control and event triggered control with reference input. The performance is approximately the same while the communication is reduced greatly in case of event triggered control. Table 5.4.1 shows different network attributes for the case of time-triggered control and event-triggered control. Three cases for event-triggered control are simulated with triggering thresholds of 0.05, 0.5 and 1. Fig. 5.11 shows the received measurement (y) for the two cases and we observe that the event-triggered transmission does not send information if there is no significant change in the measurement at plant side. Fig. 5.7 shows the controller signals for the two cases and demonstrates less controller invocations in case of event triggered control.

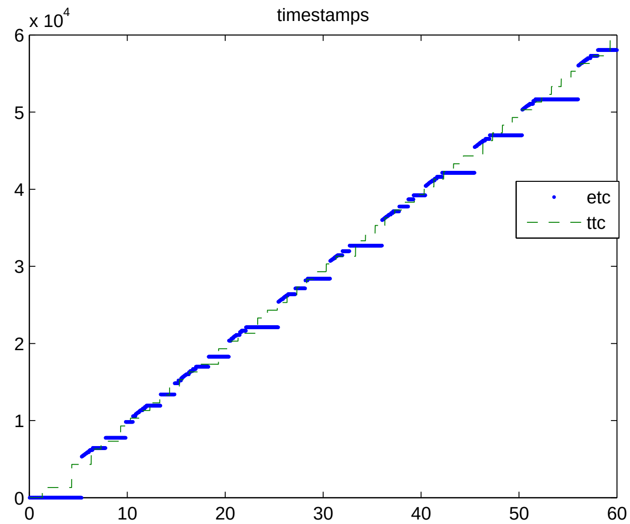

Figure 5.6: Timestamps of ETC and TTC

Table 5.1: NS-2 Network Results

Network Attribute	TTC	ETC 1	ETC 2	ETC 3
Triggering Threshould:	-	0.05	0.5	1
Packets sent:	57	51	45	25
Packets received:	56	50	44	24
Packet dropped (%):	1.754	1.961	2.222	4
Routing packets:	1	1	1	2
Routing load (%):	1.786	2.0	2.273	8.333
Avg. End-End delay (s):	0.005542	0.005569	0.005598	0.006299

The control performance for the time-triggered control and event-triggered is checked by IAE, ITAE and ISE as discussed in section 5.3.1. For ETC, we found $ITAE = 1211$, $IAE = 43.73$, and $ISE = 52.1$, while in TCC case, $ITAE = 347.1$, $IAE = 11.02$, and $ISE = 6.335$.

5.4.2 Three-cart example using Truetime simulator

The Three-Cart system is studied by [11] as an example of a Distributed Networked Control Systems. There are three carts interconnected with each other

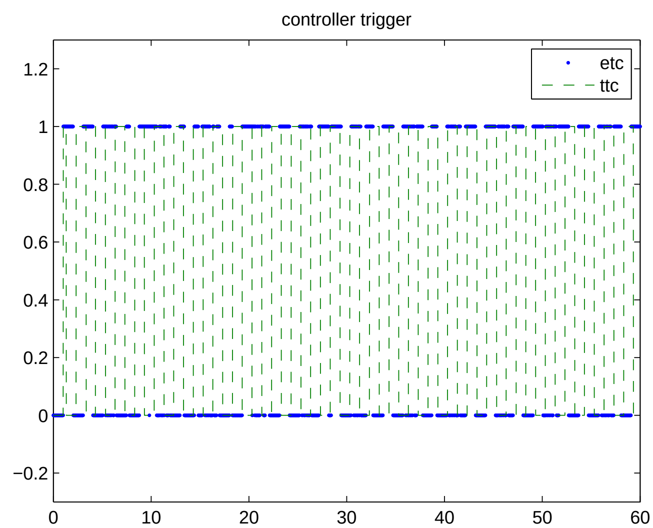

Figure 5.7: Controller Triggers for ETC and TTC

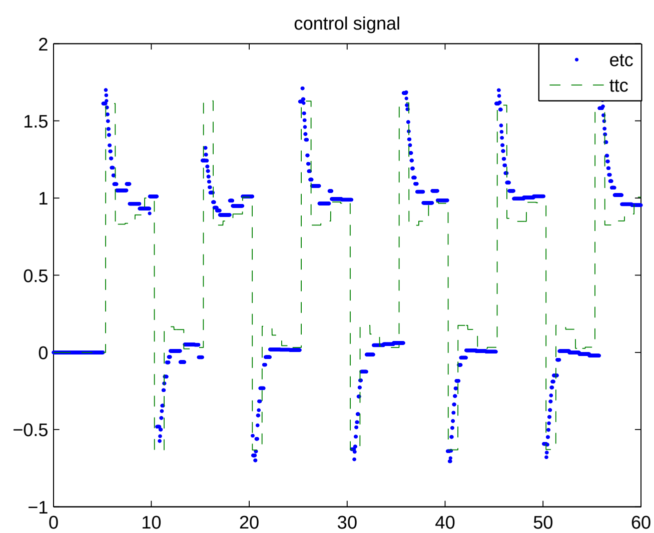

Figure 5.8: Control Signals of ETC and TTC

via spring (linear or nonlinear). They are installed with local controllers and the sensors on each cart can broadcast its position to neighbor via wireless communication network. The control for acceleration or deceleration critical with constraint like they should not collide or there becomes some unbearable tension for the springs. Simulation results for this approach to event-triggered broad-

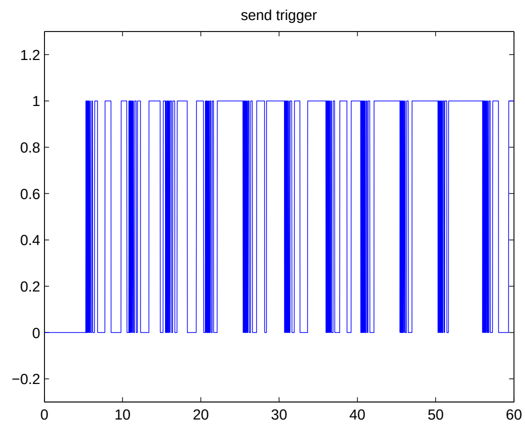

Figure 5.9: Send Triggering in ETC

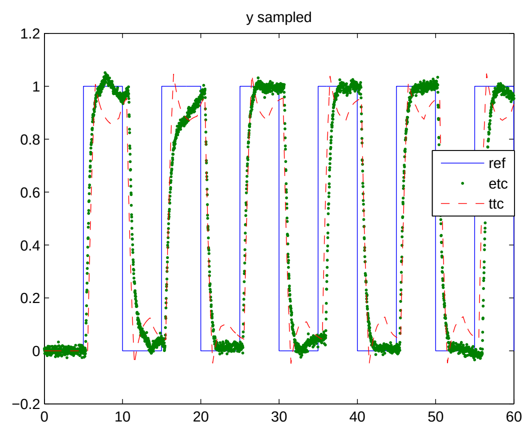

Figure 5.10: Sampled output y

casting are shown in Fig. 5.13, 5.14, 5.15, and 5.16. It consists of N carts that are interconnected through soft springs. The local state of the ith cart is $x_i = [y_i \; \dot{y}_i]^T$ where y_i is the position of the ith cart with respect to the systems equilibrium point. Assuming soft spring coupling between the carts, the state equation for the ith cart can be written as

$$\dot{x}_i(t) = \frac{d}{dt}\begin{bmatrix} y_i(t) \\ \dot{y}_i(t) \end{bmatrix}$$

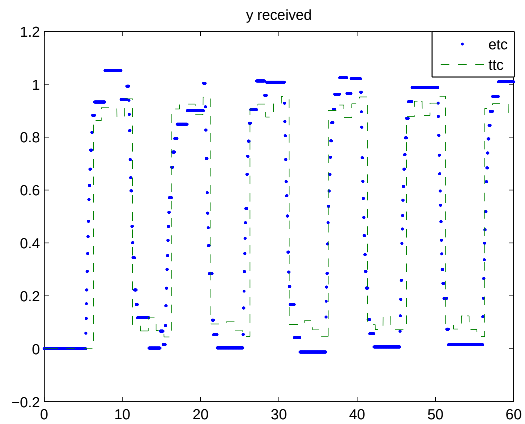

Figure 5.11: Received output y

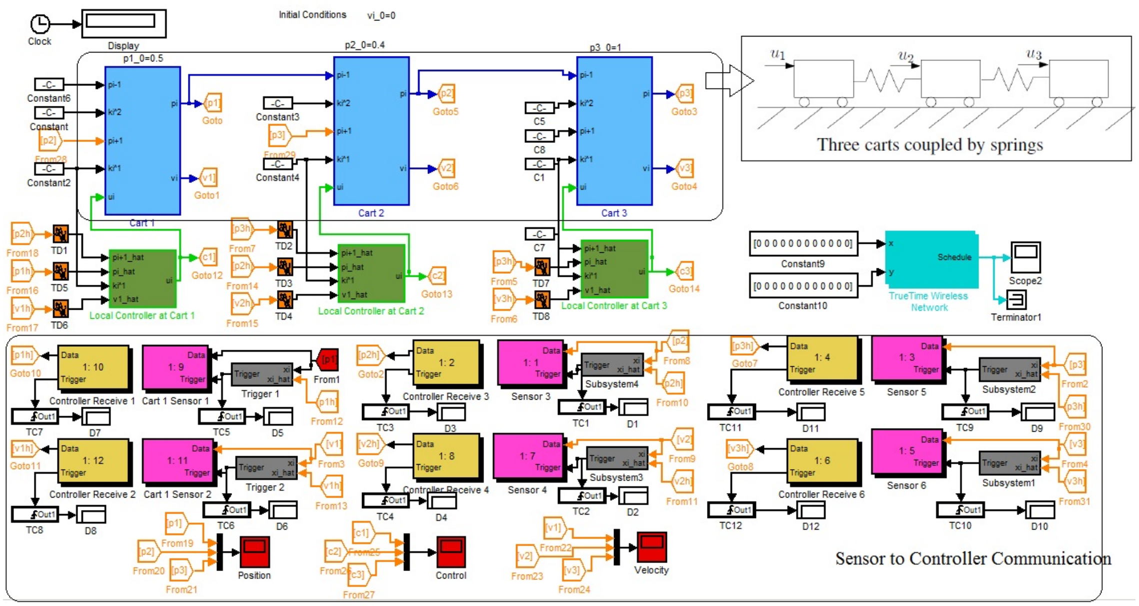

Figure 5.12: Event-Triggered Configuration of the Three Cart Example using Simulink and Truetime blocks.

where, $y_i(t) = \dot{y}_i(t)$, and

$$\dot{y}_i(t) = u_i(t) + k_i^1 tanh(y_{i+1}(t) - y_i(t)) + k_i^2 tanh(y_{i-1}(t) - y_i(t)) + w_i(t) \text{ for all } t \in R$$

where $i = 1, 2, \ldots, N$. The parameters k_i^1 and k_i^2 denote the spring constants for the springs on the right-hand and left-hand side of the ith cart, respectively. These spring constants satisfy $k_i^1 = k_{i+1}^2$ for $i = 1, 2, \ldots, N-1$. The left-end cart's spring constant is $k_1^2 = 0$ and the right-end cart's spring constant in $k_N^1 = 0$. The function $u_i : R \to R$ denotes the control applied to the cart by its local controller.

In this example, the communication network's links mirror the physical interactions between the carts so that $Z_i = D_i$. The sampled state is denoted as $\hat{x}_i(t) = [\hat{y}_i(t)\frac{d}{dt}\hat{y}_i(t)]^T$ where $\hat{y}_i(t) = y_i(r_j^i)$ and $\frac{d}{dt}\hat{y}_i(t) = \dot{y}_i(r_j^i)$ for all $t \in [r_j^i, r_{j+1}^i)$ and $j = 0, 1, \ldots, \infty$. The local control is computed from these sampled measurements as

$$u_i(t) = K_i\hat{x}_i(t) - k_i^1(tanh(\hat{y}_{i+1}(t) - \hat{y}_i(t)) - k_i^2 tanh(\hat{y}_{i-1}(t) - \hat{y}_i(t))$$

Network Settings are: Number of nodes: 12 (6 Wireless Sensors and 6 Receivers);

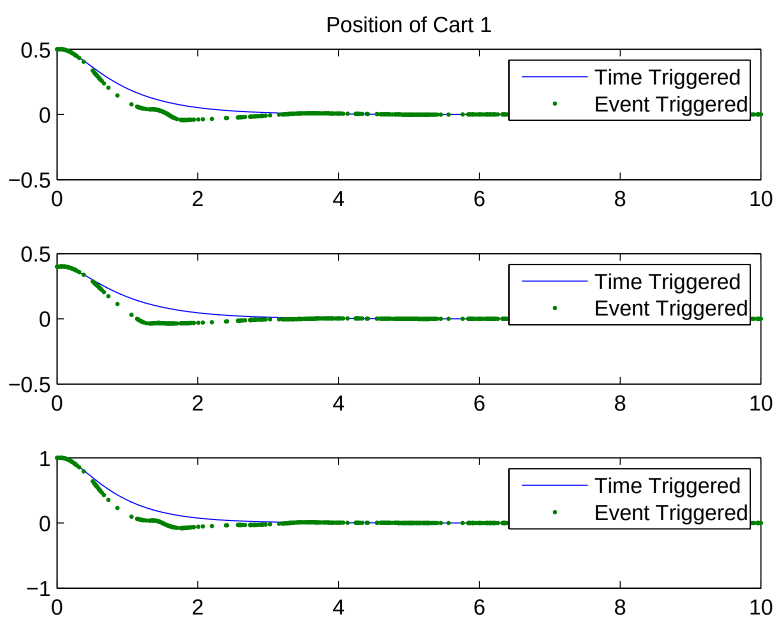

Figure 5.13: Positions of the three coupled carts

Network Type: 802.11b (WLAN); Data rate : 800000 (bits/sec); Minimum frame size: 272 bits; Transmit power : 20 (dbm); Receiver signal threshold : -48 (dbm); Pathloss exponent ($1/distance^x$) : 3.5; ACK timeout : 0.00004 (s); Retry limit

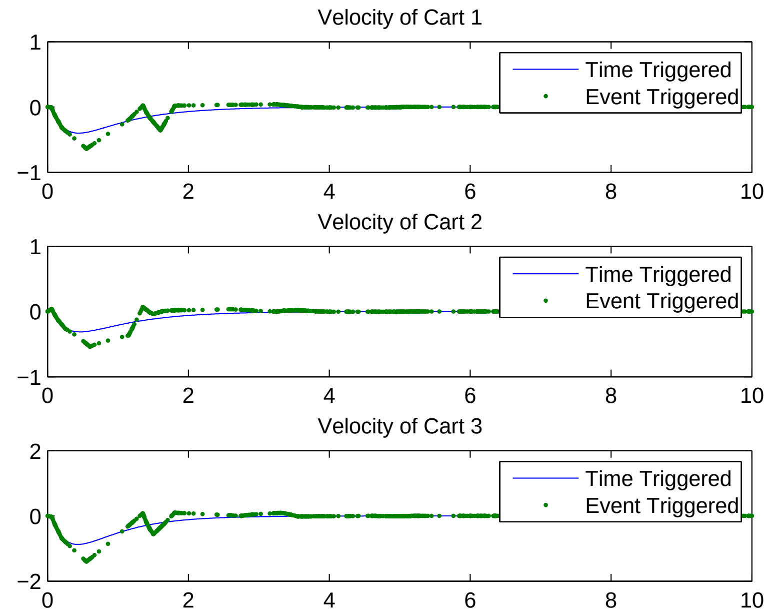

Figure 5.14: Velocities of the three coupled carts

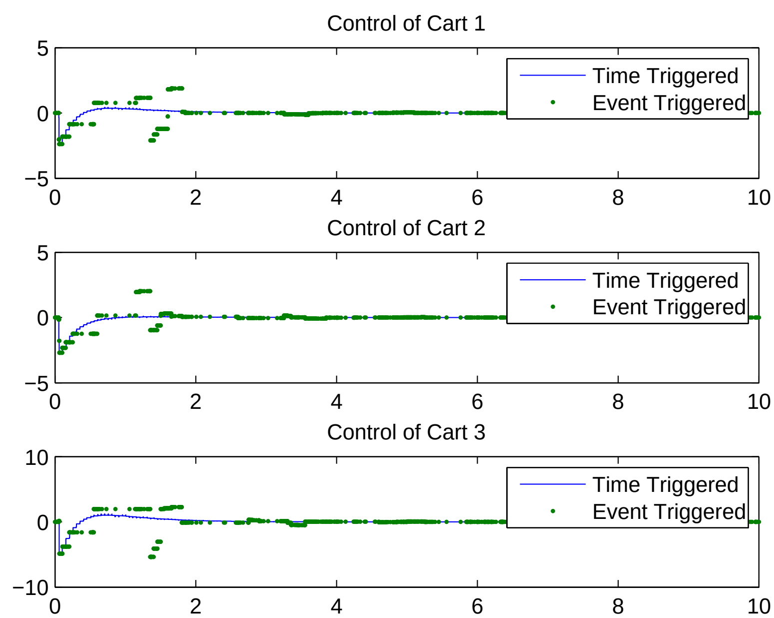

Figure 5.15: Control signals for local controllers in three coupled carts

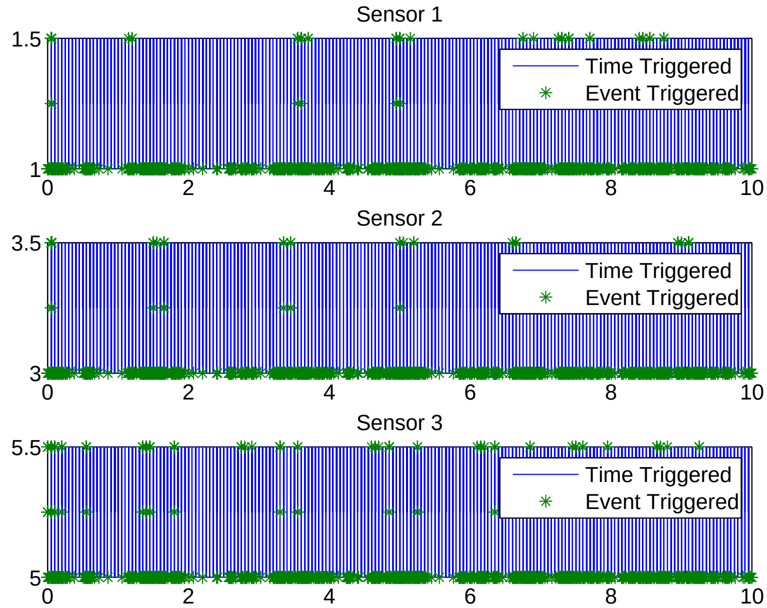

Figure 5.16: Scheduling signals for sensors 1, 2 and 3

: 5; Error coding threshold : 0.03; Loss probability (0-1) : 0.01. We run the simulation for 10 seconds. The time-triggered sampling is taken as 0.05 seconds, thus the number of time-triggered sampling results in 200 time triggered transmissions. While in Event-Triggered Control, the number of sampling is based on last communicated value and the currently sensed value at the individual sensor nodes. The mechanism for event triggering of sensors is taken from [11]. The sensors will send data when following inequality is violated. The results from this simulation are shown in Figures 5.13, 5.14, and 5.15. Figures 5.16 and 5.17 plots the scheduling signals for sensor nodes 1-6 and demonstrates the reduced number of transmission signals in case of event triggered as compared to time-triggered

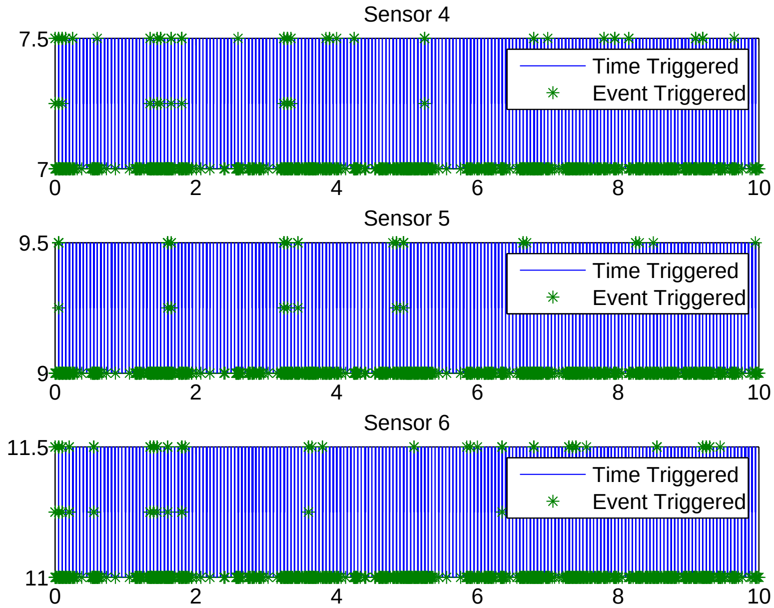

Figure 5.17: Scheduling signals of sensors 4, 5, and 6

with acceptable performance levels.

$$\|x_i(t) - x_i(r_j^i)\|_2 \leq \rho_i \|x_i(r_j^i)\|_2 \tag{5.11}$$

where $x_i(r_j^i)$ refers to last successfully transmitted state, $x_i(t)$ is the current state, $\rho_i \in (0, 1)$ with an arbitrarily taken value of 0.8 in current simulation. There are 6 wireless sensor nodes and 6 wireless receivers at the controller side. Due to the condition at each sensor node, different number of transmission events are observed. During a 10 second run, position sensor at cart 1 transmitted 15 samples, velocity sensor at cart 1 transmitted 29 samples, position sensor at cart 2 transmitted 19 samples, velocity sensor at cart 2 transmitted 28 samples, position sensor at cart 3 transmitted 14 samples, and velocity sensor at cart 3 transmitted

32 samples.

5.5 Conclusion

A comparison study for time based and event-based control has been presented. It is demonstrated that the event triggered control is better choice for distributed networked control systems despite its design and analysis complexity. This is concluded that a carefully and properly designed Event triggered control will result in efficient resource utilization with stable performance as compared to time triggered control. The fact that Event triggered control is a function of event based sampling, naturally turns the overall control problem adaptive to efficient use of resources. Event based monitoring, estimation, and control should be the first choice for multi-rate sampling systems, distributed networked systems, and wireless based systems where computational, communication, and energy resources should be used efficiently.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary

1. Distributed networked control system is implemented in MATLAB-SIMULINK-TRUETIME environment. An experimental investigation of distributed control over Ethernet network for a pilot-plant of two-tank system is also conducted.

2. Design of an event-triggered output-feedback control for distributed networked control system based on a set of LMIs is proposed. The feasible solution of the LMIs results into a stable event-triggered control system.

3. The distributed networked control system is also simulated in MATLAB-SIMULINK-NS2 environment, where plant and controller dynamics run in SIMULINK, while NS2 is used to simulate wireless communication channel

between sensor and controller.

6.2 Conclusion

Several tasks around the topic of event-triggered control and distributed networked control system are carried out from analytical development, modeling, simulation, and experiment. A comprehensive overview of the latest research interest in event based control techniques is also conducted to highlight the significant research potential. Profound challenges and potential of using event-triggered communication and control are observed for applications to distributed and wireless automation. The problem of event-triggered output-feedback control is solved in the context of distributed networked control systems in terms of LMIs. The problem of output-feedback in event-triggered case is derived as a linear matrix inequality (LMI) feasibility problem. The framework of the output based scheme is based on the local observers and the information shared by interacting (coupled) subsystems. The information sharing is based on an event condition which requires only locally observed dynamics. The control law is designed in two parts to take care of individual dynamics as well as the coupling of the subsystems. The proposed design is illustrated by using a benchmark example of three-coupled carts which shows the stabilizing results of the proposed control design. The event-triggered and time-triggered control systems are studied and evaluated over wireless networks using MATLAB-SIMULINK based simulator TRUETIME, and MATLAB-SIMULINK-NS2 based simulator PiccSIM. The performance evaluation of the event based distributed networked control systems demonstrated that the event triggered control is resource efficient choice for distributed networked control systems despite its design and analysis complexity. A carefully and properly designed event triggered control will result in efficient resource utilization with stable performance as compared to time triggered control. The fact that event triggered control is a function of event based sampling, naturally turns the overall control problem adaptive to efficient use of resources. Event-triggered communication and control should be the first choice for multi-rate sampling systems, distributed networked systems, and wireless based systems where computational, communication, and energy resources should be used efficiently.

6.3 Future Work

We end this chapter and the dissertation with the following future work.

The current work is focused on developing stable event-triggered output-feedback control algorithm for distributed networked systems.

This work can be extended to search the optimal bounds for the distributed event triggering scheme in the presented output based framework.

Study of the distributed observers including scheduling methods also has a research potential. The work can be extended to address self-triggered control and co-design methods in the framework of distributed networked systems.

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Publications

The research leading to this dissertation, also lead to the following publications.

1. Mahmoud, M.S., and Sabih, M. "Experimental Investigations for Distributed Networked Control Systems," IEEE Systems Journal, Accepted for publication and available online, doi: 10.1109/JSYST.2012.2228122, 2013.

2. Mahmoud, M.S., and Sabih, M., "Networked Event-Triggered Control: An Introduction and Research Trends", Submitted to International Journal of General Systems, Jun. 01, 2013.

3. Mahmoud, M.S., Sabih, M., Elshafei, M.A., "Event-Triggered versus Time-Triggered Networked Systems", Submitted to the Journal of IET Control Theory and Applications, Nov. 17, 2013.

4. Mahmoud, M.S., Sabih, M., Elshafei, M.A., Output-Feedback Event-Triggered Communication and Control for Distributed Networked Control Systems, Submitted to the IEEE Transactions on Parallel and Distributed Systems, Dec. 2013.

In addition, the research also lead to following publications in the closely related area of networked and distributed systems.

1. Mahmoud, M.S., and Sabih, M., An Assessment of Distributed State Estimation, In Press, International Journal of Systems, Control and

Communications (IJSCC), 2013, Vol. 5, Iss. 2, pp. 93-107, doi: 10.1504/IJSCC.2013.055976.

2. Mahmoud, M.S., Khalid, H.M., Sabih, M., "Improved distributed estimation method for environmental physical variables in static sensor networks", IET Wireless Sensor Systems, 2013, Vol. 3, Iss. 3, pp. 216-232, doi:10.1049/iet-wss.2012.0099.

3. Mahmoud, M.S., Sabih, M., and Elshafei M.A., "Using OPC Technology to Support the Study of Advanced Process Control", ISA Transactions, Third revision submitted on Oct. 7, 2013.

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